THE MINERALOGICAL MAGAZINE
AND
JOURNAL OF
THE MINERALOGICAL SOCIETY

No. 145. June, 1934. Vol. XXIII.

On zoned associations of antigorite, talc, actinolite, chlorite, and biotite in Unst, Shetland Islands.

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[Read January 25, 1934.]

Introduction.—During my mapping for the Geological Survey in 1930 of the metamorphic rocks of western Unst, numerous small masses were encountered that were composed of a central part of talc followed outwards in order by zones of actinolite, chlorite, and biotite.[1] Whilst revisiting the island in 1933 I was able to examine these associations in detail and to collect abundant material for study. As in many cases the zones are made up of a single mineral and may be a foot or so in thickness, specimens of great beauty are obtainable. It must have been from occurrences similar to these in Unst that M. F. Heddle obtained his fine examples of the various minerals from the Hillswick area of the mainland of Shetland.

It is the purpose of this communication to describe these remarkable rocks and to discuss their genesis. It will be found that they are more complete developments of an association already known from certain contacts of serpentine and acid rocks, such as those of the Lizard in Cornwall and Shabani in Rhodesia. Further, they have a very close resemblance to the soapstone bodies of the Appalachian belt of the eastern United States. The study of the Unst occurrences throws light not only upon the origin of this particular assemblage

[1] Summ. Progr. Geol. Surv. Gt. Brit., 1931, for 1930, part I, p. 67.

but also upon the general question of movement of material in metamorphism. In what follows, the masses showing this zoned arrangement are referred to as the zoned bodies.

The Country-rocks.

The zoned bodies occur in the tectonic unit that makes the western ridge of the island. This unit may be called the Valla Field block after its most conspicuous topographic feature, the high ridge of Valla Field. It is made up of a series of gneisses, mostly of sedimentary origin, with subordinate granitic and pegmatitic intrusions and permeations.

The gneisses comprise pelitic, semipelitic, and calcareous rocks that have had a long metamorphic history. There is evidence that the rocks of the whole block had been subjected to a metamorphism characterized by the production of garnet, staurolite, kyanite, and biotite in the pelitic members. After this episode, the southern portion of the block was affected by a superposed metamorphism in which these index minerals were no longer stable. They were broken down, and chlorite and chloritoid appeared in their place. Finally, the margins of the block, and certain restricted belts in the interior, were the seats of a further metamorphism associated with the dislocations limiting the block. This dislocation-metamorphism was characterized by the production of chlorite from the chloritoid of the second episode. The zoned bodies occur in areas of the gneisses that have been affected by the first metamorphism and in most cases by one or both of the succeeding. With the first metamorphic episode is associated an injection of acid igneous material, either in discrete sills and veins of granite and pegmatite or in more intimate forms that produce injection-rocks of various types.

It will be sufficient for the study of the zoned bodies to give an indication of the dominant types of gneisses found associated with them. Most of the bodies now occur amongst pelitic gneisses with conspicuous felspar blebs. These rocks recall certain similar types found in Scottish injection-complexes. They are traversed by innumerable sheets and irregular masses of pegmatitic material. The blebbed gneisses consist of biotite, muscovite, epidote, acid plagioclase, quartz, and iron oxide, and this association is stable throughout the metamorphic history of the block. Other zoned bodies are found in streaky gneisses with the same mineral composition as the blebbed gneisses; these streaky rocks are undoubtedly of injection-origin. A

few zoned bodies are closely associated with thick granite sills, whilst others are intimately connected with a group of injection-rocks characterized by large felspar ovoids. Some are found in striped hornblendic granulites traversed by pegmatites. Finally, one occurrence—that of Burgar Stack, Burra Firth—has for dominant country-rock siliceous and hornblendic rocks, but even here pegmatites are numerous.

In the first place, therefore, the zoned bodies are associated with rocks in the formation of which acid igneous material has had a share.

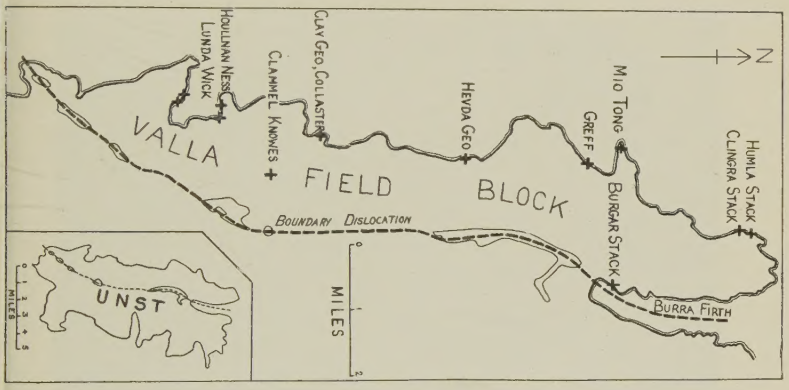

Fig. 1. Sketch-map showing the main localities of the zoned bodies in the Valla Field block, Unst.

The presence of acid injections during or soon after the production of the first metamorphism is in evidence throughout the block. The rocks of this metamorphism were most likely formed just on the margins of an injection-complex of some size; sillimanite has as yet been found only as inclusions within the garnet. In the second place, the zoned bodies are often found with hornblendic rocks of various types. As indicated in a later page, this association may be of importance in connexion with the early history of the bodies.

Field Relations of the Zoned Bodies.

The location of the larger zoned bodies within the Valla Field block is shown in fig. 1. Probably the best locality for these bodies is on the south-western shore of Lunda Wick, immediately east of Gorsendi Geo. Here purplish semipelitic and pelitic gneisses enclose a dozen or more masses. The most easterly mass (fig. 2) is the largest, being over 20 feet in diameter. The larger balls project

above the wave-washed platform of gneiss, whilst one remarkable ball (fig. 3) lies 'loose' on the platform completely detached from its country-rock. As shown in the next section of this account, many of the masses are complete, that is, they exhibit an orderly sequence of zones arranged parallel with their present margins; such masses are separated from the gneiss of the country-rock by a sharply defined surface made by the smoothed outer skin of the outermost layer, biotite. The later movements have simply smoothed the outer

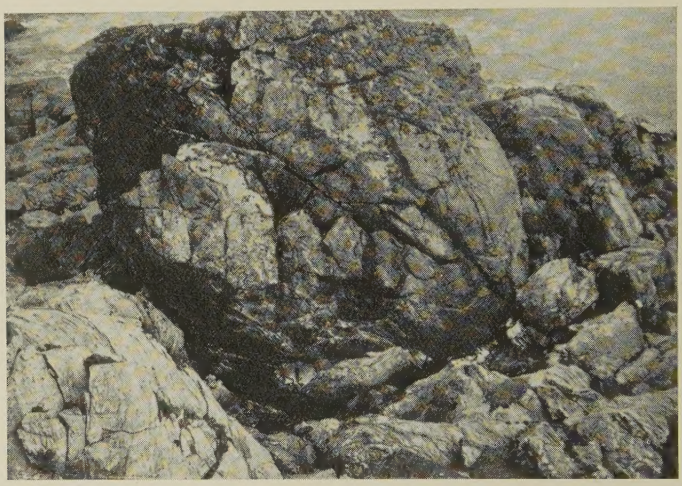

Fig. 2. Zoned body, 20 feet diameter: Lunda Wick.
(Compare fig. 5 H.)

surface without distortion of the zones. In other cases, however, the originally roughly spherical balls have been sheared out into lensed mixtures of the various constituents of the zones. For instance, a few yards westwards from the large easternmost ball, there is found a long narrow belt made up of lenticles of actinolite in biotite sheaths mixed with lenticles of gneiss, the whole being clearly a sheared-out biotite-actinolite body. Another excellent example of a distorted lensed mass is found near Gorsendi Geo; here talc, actinolite, and biotite are concerned (fig. 5 A).

On the opposite shore of Lunda Wick, along the southern coast of Houllnan Ness, dozens of small masses are encountered in flat-lying mixed hornblendic and pelitic gneisses. Here are found separate shear-streaks of biotite, chlorite, actinolite, and talc, but less distorted

bodies are seen also, the largest being 2 yards across. Noteworthy at this locality is the occurrence of masses of actinolite, 2 feet across and 6 inches thick, made up of crystals radiating from a central plane (fig. 5 B). These nodules are almost always coated with a thick skin of biotite, but small nodules lacking this biotite skin have been noted as well.

Farther north, in Wick of Collaster, knots of bronzy-coloured biotite and nodules of radiating actinolite occur in blebbed gneiss. At

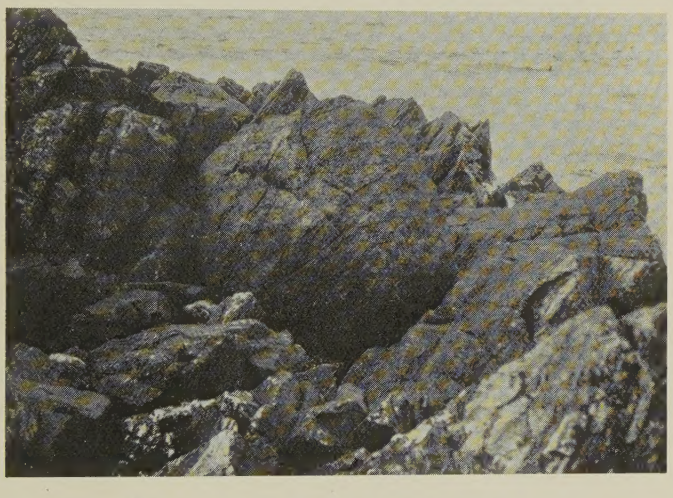

FIG. 3. 'Loose' ball, 12 feet diameter, on gneiss platform: Lunda Wick.

Ness of Collaster, in the northern cliff of Clay Geo, some good examples of the zoned bodies and their deformed derivatives are well exposed (fig. 5 J). The chief country-rock is here striped hornblende-granulite traversed by innumerable thick pegmatites. Great shear-planes run through the country-rocks and have distorted the zoned bodies and in places disrupted them into lenticular fragments. The largest zoned body is mainly composed of a lens of white talc-schist, 4 yards wide by 10 yards long, which is sheathed by black mica with an irregular zone of actinolite between. Other smaller bodies show complete zoning, whilst, on the other hand, wisps of bronzy biotite and nests of actinolite occur throughout the cliff-section. It is clear that a group of originally spherical zoned bodies has been deformed by shearing.

On the Valla Field ridge at Clammel Knowes (Clammel = Kleber = soapstone) there is an old quarry in soapstone. Relations to the country-rocks, felspar-blebbed gneisses succeeded by tourmaline-garnet-muscovite-biotite-gneiss, are not now visible.

North of Hevda Geo a few pods of radiating actinolite occur in coarse streaky garnet-mica-gneisses which are full of very coarse felspathic streaks and patches and, besides, are traversed by sheared pegmatites. These country-rocks are clearly injection-rocks.

The next occurrence to the north is found low down in the cliffs between Greff and Poindie ; it can be located west of the base of the great granite sill that makes the lower part of the Greff cliffs. The country-rocks consist of various flaggy semipelitic and pelitic schists and striped hornblendic granulites, traversed by sills of granite and in part permeated by acid materials. Conspicuous in this series of rocks is a layer of dense dull-green hornblendic rock, and it is with this rock that the zoned bodies are closely associated. These consist either of elongated balls of actinolite with biotite sheaths or else long lenses of talc-schist containing actinolite nodules and coated with a schistose mixture of talc and biotite. These masses are shreds of original zoned bodies.

Mio Tong, the point of the headland of Tonga, consists of many sheets of granite in hornblendic and micaceous schists. Between two of the granite sheets there is found a two-foot layer of bronzy-biotite rock containing balls of actinolite, whilst small radiating clumps of actinolite-prisms are not uncommon in several of the granite sheets.

Still farther north very good developments of derivatives of the zoned bodies are seen on Clingra Stack and Humla Stack at the base of the Herma Ness cliffs.[1] The section shows fine-grained hornblendic and biotitic schists and coarser felspathic gneisses invaded by sills of granite. In much of the schist there is a development of large ovoid felspars, presumably due to injection-processes. Lenses of actinolite, sheathed with biotite, and elongated masses of biotite-talc-schist are closely associated with a thick granite sheet making the landward slope of Clingra Stack. Wisps and very elongated drawn-out layers of similar material occur at many levels in the main cliff of augened and ovoid rocks opposite Humla Stack.

The last locality for the zoned bodies is on the west coast of Burra

[1] In visiting this locality, it is advisable to obtain the guidance of a local man, such as the bird-watcher of the skua sanctuary on Herma Ness, for the descent of the cliff.

Firth immediately north of Burgar Stack. The country-rocks consist of massive felspathic and siliceous granulites, with subordinate semipelitic and pelitic intercalations, and rare belts of hornblende-felspar-gneiss. Pegmatite veins, and stringers and permeations of acid igneous material, are abundant. In the cliff north of the cove in which is Burgar Stack, there is a band, some 20 feet thick, of

Fig. 4. Zoned body weathered out on shore: Lunda Wick. (Compare fig. 5 c.)

coarse hornblende-felspar-gneiss cut up by shear-planes into lenticular masses coated with biotite-hornblende-schist. Elongated masses of talc-schist, wisps of bronzy biotite, and nodules of actinolite occur in the lensed gneiss. Measurements of some of the talc lenses are 12 feet long by 5 feet thick, 10 by 1, and 10 by 3 feet; while actinolite nodules reach a length of a foot.

From this consideration of the country-rocks and field-relations of the zoned bodies it may be concluded:

i. The zoned bodies occur in a series of rocks in which acid injections and permeations are abundant.

ii. They are often associated with hornblendic rocks of various types.

iii. Two types of zoned body are separable; the first consists of the undistorted zoned type, with complete zones arranged parallel

with their present margins; the second type is formed by wisps and lenses of the materials of the zones produced by the shearing-out of the originally undistorted type.

Description of the Zoned Bodies.

Details of the Zoning.—Piecing together the evidence supplied by the complete and the relatively undisturbed zoned bodies we are led to the conclusion that these in their most complex form have the following zonal arrangement (fig. 5) from within outwards:

antigorite, talc, actinolite, chlorite, biotite.

Though the chlorite zone may be absent in some examples, the order given never varies. Representative samples of the evidence are illustrated in Sketches C, D, E, F, G of fig. 5. Sketch C of this figure shows one of the best preserved balls; it is spherical and has an interior of talc-rock, followed by a complete zone of actinolite 3 inches in thickness and then a rim of biotite 2 inches thick (fig. 4). The chlorite zone, as already mentioned, is not always present, but a perfect example is shown in fig. 5 G. From these more complex forms we may pass to the simpler actinolite-biotite associations, as illustrated in fig. 5 B. Here crystals of actinolite radiate from a median plane to form a lens-shaped nodule which is surrounded by a biotite sheath. In some examples, e.g. fig. 5 E, there is a central portion of talc-rock with prisms of actinolite. This type may indicate, as discussed below, that the process giving rise to the zoned talc-actinolite-biotite bodies has gone a step nearer finality in the actinolite-biotite bodies. It is worth noting in this connexion that the actinolite-biotite bodies are all small, all less than 2 feet in length and most of them less than 9 inches. Examples of the distorted bodies are figured in fig. 5 A, H, and J. Fig. 5 H is of the biggest ball at Lund (fig. 2). The main part of the occurrence is a central portion, 20 feet in diameter, which has an antigorite core and talc-rock margin. Around this comes a sheath of talc-schist in which are nodules of actinolite and wisps of biotite. Portions of the margins of the talc-schist are coated with a thick skin of biotite. The whole phenomenon is that to be expected from the shearing-out of an originally undistorted and complete zoned body.

Mineralogy of the Zones.

Antigorite Zone.—Rocks containing abundant antigorite and coming from the central part of the largest ball at Lund are grey-green in

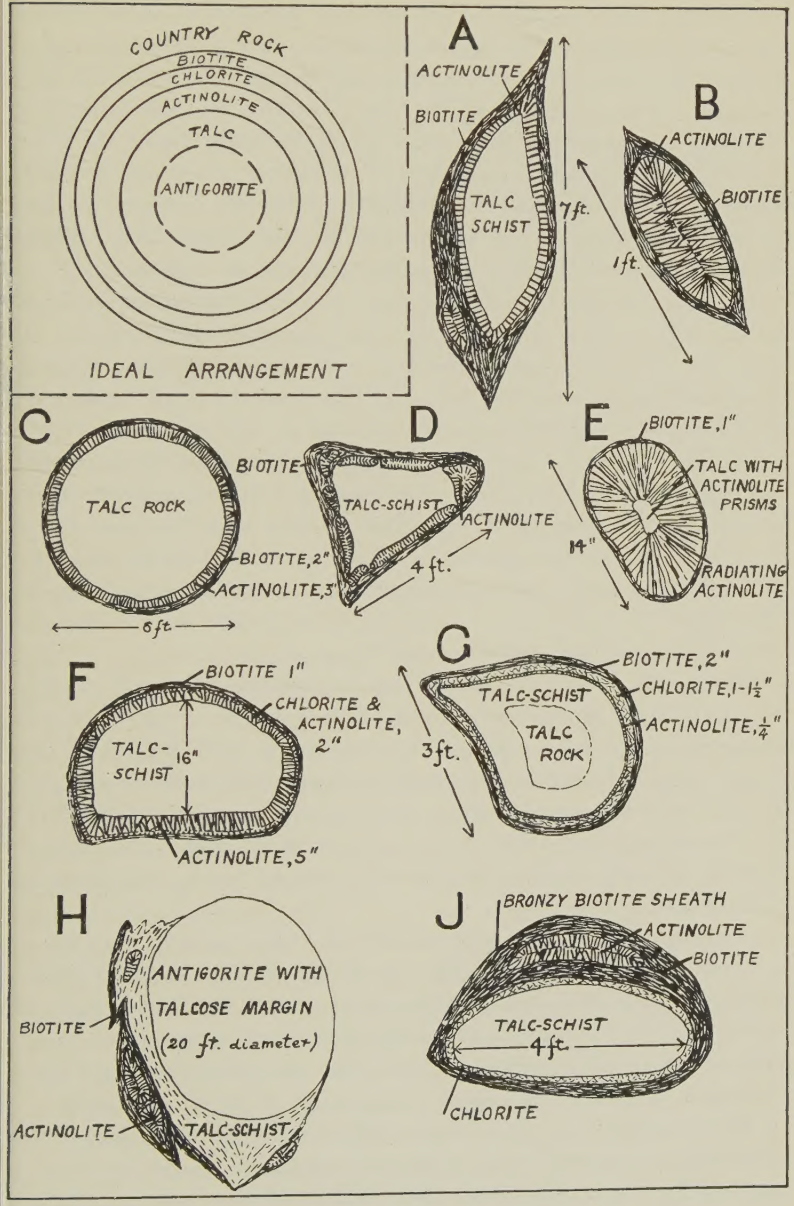

FIG. 5. Sketches of zoned bodies: Unst.

colour and fine in grain. They are seen in slice to be composed mainly of antigorite, with subordinate talc, scanty carbonate, and a few grains of iron oxide. The antigorite forms colourless plates and lamellae. The elongation of the blades is positive. The mineral is optically negative with 2V small, α along the blades 1·576. In some parts of the slice talc is abundant as colourless wisps and patches. Carbonate is also sporadic in occurrence and forms irregular patches of granules; the mineral effervesces in cold dilute acid. Black iron oxide, in collections of shapeless grains, is not common.

Talc Zone.—Rocks of the talc zone are either massive talc-rocks or foliated talc-schists. They are white or pale greenish in colour. In slice, the talc-rock is seen to be made up almost entirely of talc in a confused aggregation of wisps and flakes in which are occasional larger plates. Small grains of iron oxide are scattered evenly throughout the slice. A dusky carbonate is fairly abundant. Small nests of chlorite are not rare; it is lamellar twinned, optically positive with small optic axial angle, and faintly pleochroic from yellow to green. In the talc-schists, talc with quite subordinate chlorite, and rare iron oxide and carbonate, occur in a foliated association. The largest zoned body at Lund shows a 2-inch vein of coarsely crystalline green talc and brownish dolomite.

The portion of the talc zone immediately adjacent to the succeeding actinolite zone shows the incoming of amphibole as pale greenish flattened prisms up to an inch in length. A rock typical of this border portion has in slice large flakes of talc as its main constituent. In this occur slender colourless actinolite prisms, patches of colourless lamellar-twinned chlorite, and many small plates of a phlogopitic mica, with a strong pleochroism, brassy brown to colourless, and γ 1·594.

Actinolite Zone.—A typical member of this zone is in hand-specimen a bright-green rock made up of interlacing and subradiate crystals of actinolite that may reach a length of 3 inches. Slices of such rocks show actinolite as practically the sole component; sometimes a few small interspaces between the actinolite prisms are filled with talc or chlorite, the latter occasionally in ripidolitic forms.

The amount of talc present naturally increases at the border of the zone towards the talc zone. Similarly, at the border to the chlorite zone, when this is present, chlorite becomes an important constituent. When the chlorite zone as such is absent, a passage to the biotite zone is provided by the presence of biotite and chlorite, or of biotite

alone, in the interspaces between the actinolites. The mica occurring with chlorite has a yellow to deep brown pleochroism, and γ 1·619; that occurring alone has a yellow to greenish-brown pleochroism, and γ 1·609.

In all these rocks the actinolite forms long prismatic crystals with poor terminations. In thin sections it is colourless or pale green. Determinations with the universal stage gave 2V 82°, $\gamma : c = 15°$; by the immersion method with light from a Zeiss sodium lamp, β 1·632. These values are consistent for an actinolite having 5–6 % FeO, according to the curves given by Winchell.[1]

Chlorite Zone.—Passage rocks from the actinolite to the chlorite zone have already been noted. The main part of the chlorite zone is formed by large plates of deep-green chlorite with the following characters: very faint pleochroism, colourless to pale greenish; optical sign positive with small optic axial angle; α 1·595. The mineral is a pennine. In addition to the chlorite there may be in some rocks a very small quantity of talc or actinolite and, in a few, sparse collections of iron-ore grains or pellets of rutile.

Biotite Zone.—The biotite zone is made up of a rock which must surely be one of the most remarkable in existence. In many cases the zone consists entirely of a biotite with the following properties: pleochroism yellow to light chestnut-brown, γ 1·621. The mica here occurs as large plates with a poorly expressed alignment. In the more foliated type of biotite sheath, the mineral shows a different pleochroism, almost colourless to pale yellow-brown, and γ 1·614.

The nature of the margins of the biotite zone against the country-rock is a subject of importance. One type of margin is clean-cut and consists of the smoothed outer surface of the biotite sheath itself. The actual separation surface is usually plastered with a bronze-coloured biotite with γ 1·627, cleavage flakes in oils being deep brassy-yellow. In other examples there appears to be a passage into the country-rock. One such passage rock shows a biotite similar in optical properties to that making the main part of the zone (γ 1·621), but between the biotite plates occur shapeless grains of oligoclase. The amount of felspar increases towards the country-rock side until a normal oligoclase-biotite-gneiss is reached. In another passage-rock, the transitional portion is formed of biotite and muscovite, with abundant epidote. Such a rock differs from the country-rock adjacent to the occurrence only in the absence of plagioclase. These

[1] A. N. Winchell, Elements of optical mineralogy. 1927, pt. 2, p. 211.

passage rocks are of importance in the consideration of the genesis of the zoned bodies.

Comparison with similar associations in Shetland and elsewhere.

What is most likely a zoned association essentially similar to those of Unst occurs on the south bank of the Niddister Burn on Ness of Hillswick in the north mainland of Shetland. The present writer has not visited this locality, but the similarity is evident from the sketch of the field-relations given by F. Coles Phillips.[1] According to Phillips the country-rocks are gneisses with veins of reddish granite. If this Hillswick occurrence is a zoned body then serpentine is followed outwards by a 2-foot belt of anthophyllite, this by soapstone and then talc-schist against the country-rocks. Until the field-relations and metamorphic history of the country-rocks are better known it is impossible to decide whether this sequence is original or mechanical, but the occurrence is important because Heddle[2] has given analyses of serpentine, talc, anthophyllite, actinolite, chlorite, and biotite from this locality. From Heddle's notes on the mode of occurrence of the analysed minerals it is clear that they are closely associated in the field and, accordingly, the analyses may be employed in the discussion of the Unst phenomena. Phillips concludes that the anthophyllite and talc belts arise by the introduction of material, mainly silica, from the neighbouring intrusive veins. This origin of anthophyllite-schists has been characterized by A. Harker[3] as a 'quite gratuitous hypothesis'.

For somewhat analogous occurrences in the Lizard, transfer of material has been shown to occur by Sir John Flett.[4] Here, at the contact with igneous gneiss, serpentine is altered to a soft greenish rock consisting mainly of talc and tremolite, sometimes with anthophyllite and chlorite. Smaller inclusions in the gneiss are talc-tremolite-chlorite-schists. Flett concludes that two agencies have been in operation, an impregnation of the serpentine by hot vapours or liquids given off by the gneisses on cooling, and also mechanical shearing.

[1] F. C. Phillips. The serpentines and associated rocks and minerals of the Shetland Islands. Quart. Journ. Geol. Soc. London, 1927, vol. 83, p. 642.

[2] M. F. Heddle, Min. Mag., 1879, vol. 3, p. 18; and The mineralogy of Scotland. Edinburgh, 1901, vol. 2.

[3] A. Harker, Metamorphism. London, 1932, p. 276.

[4] J. S. Flett, The geology of Lizard and Meneage. Mem. Geol. Surv. England and Wales, 1912, Explan. Sheet 359, pp. 141–142.

In his account of the Shabani asbestos deposits of Southern Rhodesia, F. E. Keep[1] considers that serpentine is there formed by the action of magmatic waters accompanying an intrusion of granite. In the later hydrothermal stage, talc-carbonate-rocks are produced, whilst actinolite-rock arises by a similar introduction of material from the acid rock. Keep gives references to several actinolite occurrences that, in their field-relations, support this explanation.

The celebrated Vermont talc deposits have been considered by J. L. Gillson[2] to be of replacement origin. Gillson believes that hot alkaline solutions, low in silica and towards the last rich in magnesia and carbon dioxide, have there replaced not only serpentine but even sedimentary gneisses. In the latter case it is supposed that the gneiss is converted into chlorite and amphibole and then these changed into talc. The time-sequence given by Gillson is tourmaline, quartz, biotite, apatite, actinolite, chlorite, dolomite, talc, magnetite, and pyrrhotine. From the accounts and discussion of these Appalachian soapstone and talc deposits recently given by H. H. Hess[3] it is obvious that they are practically identical with the Unst zoned bodies. Hess considers that dilute solutions, consisting simply of water and carbon dioxide and emanating from an acid intrusion, were responsible for the change of gabbro to amphibolite, and of ultrabasic rock to actinolite-rock, chlorite-actinolite-rock, and soapstone. These changes took place with falling temperature, the time-sequence of the minerals being hornblende, actinolite, chlorite, talc, and carbonate.

The Origin of the Unst Zoned Bodies.

If, following Harker, it is considered that no transfer of material has taken place, then the question of the original pre-metamorphism nature of the bodies must be examined. The present writer finds it difficult in this event to suggest what such bodies could have been. If they were of sedimentary origin, they must have been concretions of extraordinary size and of a remarkable zoned composition. If they

[1] F. E. Keep, The geology of the Shabani mineral belt, Belingwe district. Bull. Geol. Surv. Southern Rhodesia, 1929, no. 12, pp. 78, 82, 104, 105, 106. [Min. Abstr., vol. 4, p. 181.]

[2] J. L. Gillson, Origin of the Vermont talc deposits. Econ. Geol., 1927, vol. 22, p. 246.

[3] H. H. Hess, Hydrothermal metamorphism of an ultrabasic intrusion at Schuyler, Virginia. Amer. Journ. Sci., 1933, ser. 5, vol. 26, p. 377; and The problem of serpentinization and the origin of certain chrysotile asbestos talc and soapstone deposits. Econ. Geol., 1933, vol. 28, p. 634. [M.A. 5–441.]

were of igneous parentage, they must have possessed some kind of gigantic orbicular or shelled structure. Further, whether they were originally sedimentary or igneous, they have on metamorphism preserved their primary compositional zoning and the arrangement of this zoning with respect to their present peripheries. All these possibilities and combinations of possibilities seem to the writer to be extremely unlikely.

It is suggested, therefore, that movement of material has taken place. The regular arrangement of the zones in relation to the present boundaries of the bodies clearly indicates this. What has been the nature of this transfer of material? A satisfactory answer to this question depends mainly on two points: the original composition of the unzoned body and the original limits of this. It is reasonable to hold that the bodies consisted originally of ultrabasic material, probably peridotitic in character. The existence of an antigoritic central portion, and the presence of so many magnesia-rich minerals in the assemblage, support this view. With regard to the second point, the original limits of this peridotitic ball, several aspects of the field-relations must be considered. The sharp boundary of the outermost layer, biotite, seen in most cases against the country-rocks suggests at first sight that here was the original limit of the peridotitic ball. But these bodies have been subjected in many instances to one or two later metamorphisms in which stress was a dominant factor, so that the sharp margins now found may be of mechanical type; slipping has taken place on the most likely surfaces. That such may be the case is indicated by the existence in a few localities of passage zones between the biotite layer and the country-rock. Where, then, was the original margin of the peridotite ball? This question cannot be definitely answered; all that can be done is to advance certain suggestions that have a bearing on the answer.

In the discussion of the possible transfers in the production of the Unst bodies, one may conveniently use the analyses by Heddle, early though they are, of the constituent minerals of the Ness of Hillswick occurrence. In the table below, these analyses are given, together with two analyses of the Unst country-rocks. It may be objected that the Hillswick minerals are possibly not of the same composition as those of Unst and may not have had an entirely comparable origin. If this objection is sustained, then it may be pointed out that the minerals of the zones are sufficiently well characterized and sufficiently different from each other in composition for their average

values to be used in this discussion. Whether Heddle's compositions or the theoretical compositions are used, the conclusions concerning the general trends of the transfer are the same. The data listed in the table are shown in fig. 6, where Heddle's compositions of the minerals are plotted in the order in which they make up the Unst zoned bodies, the innermost zone, serpentine, being at the top and the outermost, biotite, at the bottom. The compositions of the Unst country-rocks from analyses by Mr. B. E. Dixon, H.M. Geological Survey, are shown below the biotite.

Compositions of the Minerals of the Zones.

	SiO_2.	Al_2O_3.	Fe_2O_3 + FeO.	CaO.	MgO.	K_2O.	Na_2O.	H_2O.
Serpentine	41·46	0·01	3·58	—	41·76	—	—	12·43
Talc	60·89	4·14	1·24	—	28·09	—	—	4·72
Actinolite	55·00	1·51	4·45	10·38	23·31	1·12	1·10	2·90
Chlorite	39·81	11·43	7·97	2·80	25·64	1·20	3·15	7·91
Biotite	39·80	14·19	14·17	0·10	18·32	8·43	2·11	2·52
Blebbed gneiss ...	64·46	14·60	6·55	3·50	2·78	3·31	2·62	0·71
Staurolite-kyanite-garnet-gneiss ...	55·79	25·17	9·60	0·68	1·93	3·00	1·12	1·39

Inspection of the table and of fig. 6 leads to certain indications of the course of the movement of material. Let it be assumed for the present that the margin of the peridotite or serpentine ball was situated at the *outer* margin of the biotite zone. First, it is clear that magnesia and water have left the ball. It may be recalled that in the case of the Lizard serpentine-gneiss contact, Flett (loc. cit., pp. 143–144) has shown that magnesia-rich solutions have given rise to pseudophite from the alkali-felspar of the adjacent rock; a soapstone with 31·08 % MgO replaces granite. Second, it seems likely that silica has been introduced into the ball, but has been concentrated in the interior layers. The serpentine centre and the chlorite and biotite outer layers have the same silica percentages, whilst the intervening zones show greatly increased percentages with a maximum at the talc zone. It could be suggested, however, that no influx of silica has taken place, but that talc and magnesite were produced by the reaction of introduced carbon dioxide and the serpentine centre. If this has been so then the magnesite has been almost entirely removed, for examination of slices shows that carbonate occurs only sporadically and in small quantity in the talc zone and, except for rare and thin dolomite-talc veins, appears to be calcite. An analysis

of the Hillswick soapstone given by Phillips (loc. cit., p. 643) shows no carbonate. It is preferable, therefore, to consider that an introduction of silica has taken place, perhaps accompanied by some carbon dioxide. Third, lime has also been introduced and has collected almost entirely in the actinolite zone. The most remarkable point about the movements of these components is the formation of the silica maximum in the talc zone and the accumulation of practically all the imported lime in the actinolite zone. Continuing the assumption that the outer margin of the ball was at the outer margin of the biotite zone, then in the formation of the chlorite and biotite zones there has been an introduction of alumina, iron oxides, and alkalis into these zones, pari passu with the outflow of magnesia and water.

The alternative assumption that the original outer margin of the peridotite ball was not at the outer margin of the biotite zone must now be considered. The other positions that appear possible are at the *inner* margin of the biotite zone or slightly farther in so as to include a narrow portion of the chlorite zone when this is present. We have already noted that there is a certain amount of evidence in favour of regarding the country-rock, blebbed gneiss, as influenced by injection-metamorphism, so that any suggestions with respect to the original nature of the country-rock are difficult to make. In the production of similar blebbed gneisses in certain injection-complexes, a transfer of silica, lime, and soda, or of oligoclasic material, has been considered likely.[1] In order to proceed with this discussion, let us assume, therefore, that the original country-rock had the composition of the blebbed gneiss less a certain amount of silica, soda, and lime. Except for alumina, it might have had a composition like that of the staurolite-kyanite-garnet-gneiss, another country-rock of the zoned bodies. To produce the biotite zone from such a forerunner of the blebbed gneiss requires an addition of magnesia, iron oxides, and alkalis, and an outflow of silica and lime. Except for the field-fact that the biotite zone never exceeds 9 inches in thickness whilst the actinolite zone may be 2 feet thick and the talc zone a dozen feet or

[1] V. M. Goldschmidt, Die Injektionsmetamorphose im Stavanger-Gebeit. Vidensk.-Selsk. Skrift. Kristiania, 1921, for 1920, no. 10.

T. Vogt, Sulitelmafeltets geologi og petrografi. Norges Geol. Undersök., 1927, no. 121, p. 491.

H. H. Read, The igneous and metamorphic history of Cromar, Deeside, Aberdeenshire. Trans. Roy. Soc. Edinburgh, 1927, vol. 55, p. 317; and The geology of central Sutherland. Mem. Geol. Surv. Scotland, 1931.

more, it could be suggested that this outflowing lime and silica passed into the balls to form the actinolite and talc zones. It is preferable, however, to consider the lime and silica of these zones as coming in the main from outside the biotite zone.

To choose between the two positions of the outer limit of the original peridotite ball is a difficult task. Hess,[1] in describing the

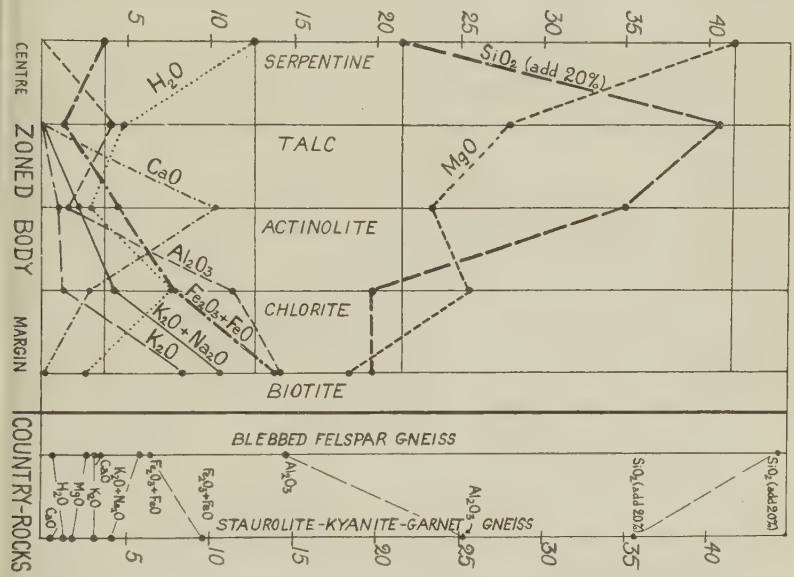

Fig. 6. Graph of suggested chemical compositions of the zones of the zoned bodies; and analyses of the country-rocks.

talc deposit of the Mineral Products Company, Chester, Vermont—a deposit presenting very close similarities to the Unst zoned bodies—states that the biotite sheath represents approximately the original contact of the ultrabasic with the country-rock. In a later page, however, whilst presumably referring to the same type of deposit, he considers biotite to be a 'hybrid mineral; instead of being composed of elements derived from the ultrabasic as are the minerals of the characteristic series, it derives its potassium from the acid intrusive and its magnesium from the ultrabasic' (loc. cit., p. 646). The well-established production [2] of biotite in amphibolites in injection-com-

[1] H. H. Hess, Econ. Geol., 1933, vol. 28, pp. 643–644.

[2] References are given in H. H. Read, Trans. Roy. Soc. Edinburgh, 1927, vol. 55, p. 346.

plexes has a bearing on this discussion of the original outer limits of the balls.

On account of the existence of transitions between the biotite zone and the country-rocks the present writer prefers to consider the biotite zone as belonging to the country-rock side of the original junction. If this were so, and assuming as reasonable from the field-evidence that no change in volume took place in the original ball during the transfer, then the following movements of material have taken place:

1. Magnesia leaves the peridotite ball and is concentrated in the immediately adjacent layer of the country-rock to help form the biotite zone.

2. Silica enters the ball, and is concentrated in the interior zones, forming a maximum in the talc zone.

3. Lime enters the ball, and is concentrated almost entirely within the actinolite zone.

4. Alumina enters the ball, and is concentrated in the chlorite zone.

5. Soda enters the ball and, from Heddle's analyses, is found in the chlorite and actinolite zones.

6. Iron oxides and potash are concentrated in the biotite zone. In this case, the iron oxides may have been turned out of the ball, but potash cannot have been.

7. Water leaves the ball.

8. Some carbon dioxide may enter the ball at some period to form with lime the sporadic carbonates of the talc zone.

The zones of the Unst zoned bodies therefore arise as follows:

Antigorite zone, with MgO and H_2O maxima, is a relic of the original peridotite body, modified, of course, by stress metamorphism.

Talc zone, with SiO_2 maximum, is formed by the inflow of SiO_2 and expulsion of MgO and H_2O from the peridotite body.

Actinolite zone, with CaO maximum, is formed by inflow of SiO_2 and CaO and outflow of MgO and H_2O.

Chlorite zone, with Al_2O_3 maximum, is formed by inflow of Al_2O_3 and expulsion of MgO and H_2O.

Biotite zone arises from the country-rock, by inflow of MgO, K_2O, and possibly iron oxides, with outflow of SiO_2, CaO, and Al_2O_3.

A few of the many points that arise from the contemplation of this complex mechanism may be examined. In the Appalachians, the mineral time-sequence—actinolite, chlorite, talc, and carbonate—has

been demonstrated for innumerable deposits over a great area. Such a time-succession takes place with falling temperature. At a high temperature, actinolite will be the first mineral to form, and at any lower temperature the appropriate member of the succession will be produced. Thus, in the production of the Appalachian associations, the sequence of events is first the high-temperature alteration of the peridotite ball to actinolite; as the temperature falls the actinolite is replaced by chlorite, and at the lowest temperature by talc and carbonate.

When an attempt is made to explain the Unst zoned bodies on the Appalachian basis, great difficulties are encountered. Three features of the Unst bodies may be recalled: first, talc occurs always in an interior position; second, extremely narrow zones of actinolite and chlorite (e.g. in fig. 5 C, F, G, H) continue completely round large balls; and third, most of the smallest balls consist only of actinolite and biotite. From these features it appears extremely unlikely to the present writer that the peridotite ball has been completely made over into actinolite, then an *outer* margin converted into chlorite, and then the *interior* changed into talc, leaving unreplaced a very narrow but continuous zone of actinolite of uniform thickness, and, further, that this has happened in several distinct balls. Finally, if the Appalachian sequence was valid for Unst, the smallest bodies remained unchanged as the temperature fell, whilst the interiors of the larger bodies were altered. If the minerals of the Unst balls are not of simultaneous formation, then it could be suggested on the field-evidence that the time-sequence was talc, actinolite, chlorite, the whole of a ball having been made over into talc, then the outer portion of the talc made into actinolite, and then the outer portion of the actinolite made into chlorite. Though in some thin sections there is some evidence of a small degree of replacement of actinolite by talc at certain talc-actinolite zone margins, it must be remembered that these bodies have suffered two metamorphisms at least. The individual zones are of sufficient thickness and purity to show that transfer of material has taken place on a considerable scale; such transfers become remarkably complex if the zones are held to be of successive formation; it is sufficient in this connexion to point out how involved the movement of lime must have been if the zones were formed one after the other. In the writer's opinion, the field and microscope evidence shows that the minerals of the different zones were of simultaneous formation.

If this were so, then the production of the zones can be considered as a kind of 'aureole-effect', conditions varying from margin to centre of the ball. The formation of each zone depends upon the physical and especially upon the chemical factors operative at any given position within the ball. In this 'aureole' the inner part of the ball corresponds to the outer part of the normal contact-aureole; in this inner part the physical conditions of temperature and pressure were suitable for talc formation when combined with the chemical factors, inflow of silica and outflow of magnesia, and similarly for the other monomineralic zones. The anomalous position of the chlorite zone in the Unst balls when compared with the Appalachian bodies is not anomalous when it is considered as chemically controlled by the supply of alumina from the outside.

Perhaps the most remarkable result of the interchanges of material is the virtual spacing of the introduced oxides, silica in advance of lime, lime in advance of alumina. I do not wish to conclude that silica as such passed more rapidly into the ball than lime as such, but the final adjustments of whatever transitional compounds were formed have been to cause these spaced maxima. This spacing recalls the interesting account given by F. D. Adams [1] of the transfusion of material between two bricks, one magnesite and the other dolomitic magnesite and mill-scale (largely Fe_3O_4) when burnt in a laboratory kiln. Silica and alumina have accumulated in the magnesite brick farthest from the contact, whilst lime 'has been carried through the substance of the brick and been deposited in progressively larger amounts in it as the distance from the contact increases, rising . . . to 6·3 % . . . beyond which the alteration ceases and the lime falls at once to 2·4 % which is the lime content of the unaltered brick' (loc. cit., p. 158). Further, there is produced a concentration of ferric oxide and magnesia near the contact of the two bricks. Such a spacing out of oxides recalls in type that of the Unst bodies; especially interesting is the comparable behaviour of lime in the two cases. J. W. Greig [2] has described a similar type of concentration in silica bricks used in the roofs of open-hearth steel furnaces. Such bricks become zoned, with an outside portion corresponding in composition to the original brick, followed by a zone in which there is a

[1] F. D. Adams, The transfusion of matter from one solid to another under the influence of heat. Canadian Journal of Research, 1930, vol. 2, p. 153.

[2] J. W. Greig, On liquid immiscibility in the system FeO–Fe_2O_3–Al_2O_3–SiO_2. Amer. Journ. Sci., 1927, ser. 5, vol. 14, pp. 483–484.

concentration of lime and alumina, and then by a zone much higher in iron oxide.

The transfusion of the oxides into the peridotite balls of Unst is undoubtedly connected with the injection of acid material into the country-rocks. The evidence for such an acid injection-process has already been outlined. The various types of injection-rocks—blebbed gneisses, gneisses with felspar ovoids, permeation-gneisses and the like—and the ubiquitous pegmatitic and granitic intrusions are all characteristic of injection-complexes. The country-rocks have been soaked in juices which it is reasonable to believe were the same as those concerned in the production of similar injection-complexes, such as those of Stavanger, Cromar, central Sutherland, and elsewhere, that have been chemically studied. Such fluids, composed of silica, soda, lime, and probably alumina, have entered the peridotite ball, travelled into it at various speeds or become fixed at various positions, and so have brought about the zonal arrangement of the minerals formed; at the same time, magnesia has left the ball and, with the help of alkalis of injection-origin, has reacted with the country-rock to form the biotite zone.

Summary of the History of the Unst Zoned Bodies.

We are now in a position to consider the whole history of the zoned bodies.

(1) Their original rocks were most likely small intrusions of ultrabasic character of the geosynclinal phase;[1] they were as usual associated with basic intrusions typical of this phase and with what were most probably basic tuffs.

(2) The movement phase now began. The resulting metamorphism culminated in the production of the garnet-staurolite-kyanite-gneisses in the pelitic rocks of the area; at the same time the basic and ultrabasic intrusions of the geosynclinal phase were separated into small bodies, lens-shaped in the case of the basic rocks, more spherical with the ultrabasic rocks. The basic tuffs were converted into striped hornblendic schists and granulites, the basic rocks into amphibolites and the ultrabasic rocks into serpentine.

(3) In the later stages of this high-grade metamorphism, the country-rocks were permeated by acid materials and invaded by granite and pegmatite. Fluids of this injection-period entered the ultrabasic masses and formed the zonally arranged layers of the

[1] H. H. Read, Trans. Roy. Soc. Edinburgh, 1927, vol. 55, p. 351.

zoned bodies. Material displaced from these reacted with the country-rock and the injection-fluids to give the biotite zone.

(4) One or two metamorphisms, both marked by great stress and moderate temperature, later affected the rocks of the region. One result was in most cases to pare away the transitional zone between the biotite zone and the country-rock and to form a sharp boundary marked by the development of bronzy biotite. In other cases, the zoned bodies were distorted or even sheared into elongated masses made up of wisps of the minerals of the various zones. When we reflect how vulnerable bodies of this nature enclosed in sedimentary gneisses of high grade must have been, we must be astonished at the perfection of preservation in so many instances of the zoned character.

The writer wishes to emphasize one aspect of this communication, namely, that in injection-metamorphism movement of material takes place on a considerable scale. This conclusion had already been reached by the study of sedimentary hosts in injection-complexes; this account of similar transfers in connexion with an ultrabasic host leads to the same result but uses more spectacular subjects.

Finally, I desire to express my thanks to Mr. I. S. Double, of the Geological Department, University of Liverpool, for help in the field, and to Dr. W. Q. Kennedy, of H.M. Geological Survey, for constructive criticism.

Zoning in plagioclase felspar.

(With Plate XXII.)

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[Read January 25, 1934.]

DURING the examination of the basalts of Calciferous Sandstone age which are mapped on the one-inch Sheet 23 (Hamilton, Lanarkshire) Scotland, the peculiarities of zoning exhibited by the porphyritic felspar were studied in some detail. As only a summary of the details is possible in the memoir explanatory of the geology of this Sheet, the description of the zoning is offered here, and some conclusions regarding the magmatic history of the zoned felspars are presented.

The basalts are all olivine-basalts, in some of which felspar is the only porphyritic constituent (Markle type), while others carry phenocrysts of augite and olivine in addition (Dunsapie type); all three minerals may be only microporphyritic (a transitional type lettered vyBd[1] on the geological map). The groundmass of the basalts is composed essentially of laths of labradorite, which is usually not zoned and contains about 50 % An, together with grains and crystals of augite and iron-ore, interstitial serpentinous material, and more or less felspathic cement of oligoclasic composition.

In Section I of the paper the zoning is described and three types of zoning, termed here normal, simple reverse, and oscillatory, are distinguished. The complicated problem presented by oscillatory-zoned plagioclase is discussed in Section II.

I. *Zoning of felspar in Scottish basalts.*

According to the theory of continuous reaction between crystal and magma the plagioclase separating out from a magma of basaltic composition should show, in the event of incomplete establishment of equilibrium, a progressively more albitic composition towards the periphery. This change in composition is observed in many igneous rocks and may take place continuously so that the crystal shows no

clearly separated zones. The change may also proceed discontinuously, with the consequence that the crystal exhibits more or less sharply separable zones within each of which the composition remains constant, while the zones become more sodic towards the exterior. Zoning, whether continuous or discontinuous, which effects a change from calcic to less calcic plagioclase outwards from the centre of a crystal may be considered normal zoning. Cases are, however, found in which the felspar of the outer zone is more calcic than that of the inner zone. This zoning is reverse zoning. No observation has been made of continuous outward change from less to more calcic felspar, but occurrence of more calcic shells around and sharply demarcated against cores of less calcic plagioclase felspar is frequent in the basalts under consideration. Reference in the following pages to zoning of this kind will be made under the term simple reverse zoning.

Almost as common as normal and simple reverse zoning is a complex zoning (pl. XXII, figs. 1, 2, 3, 6) in which there is greater difference in composition between adjacent than between the alternate zones. The felspar crystal is built of thin shells alternately less and more calcic, and is said to be zoned in an oscillatory manner. The zones are usually sharply demarcated from one another. Oscillatory zoning is typically discontinuous and in detail consists of repetitions of discontinuous normal and discontinuous reverse zoning. The mean composition of two adjacent zones may remain steady over several zones, but in most cases eventually shows progressive change along the crystal. This change may be towards a more sodic plagioclase in the outer part, and the crystal has then oscillatory-normal zoning; the change may, on the contrary, be towards more calcic plagioclase, and the crystal has then oscillatory-reverse zoning.

In 135 thin sections of basalts in which zoning of felspar might be expected on account of coarseness of texture or presence of phenocrysts, it was found that normal zoning was present in 34, simple reverse zoning in 41, while oscillatory zoning was observed in 18 of this aggregate number. In some of the remaining 60 sections zoning was not present, in others it was too obscured by decomposition or by included material for specific determination.

Normal Zoning.—The simplest type of normal zoning is shown by felspar laths which constitute the groundmass of coarse-textured basalts (19640, 21195)[1] and by phenocrysts of idiomorphic prismatic

[1] The numbers refer to registered slices in the Geological Survey Collection of Scottish rocks.

habit (19386, 23987). The zoning is continuous in these specimens and occurs towards the termination of the laths or prisms, that is, in the direction in which growth was most rapid. Usually the zoned portion forms from one-quarter to one-half the total length of the crystal. On rotation between crossed nicols the zoned portion shows continuous and unidirectional change in position of extinction.

In many sections, however, zoning of a discontinuous type is exhibited by the phenocrysts. The bulk of the crystal is often of homogeneous calcic plagioclase which is bordered by a narrow homogeneous but less calcic zone, usually broader in the direction of the *c*-axis but distinct all round the crystal. There is no transition from the inner to the outer portion. The line of separation is parallel to the idiomorphic crystal outlines (19313, 19316) and is, in a narrow beam of light, shown up by the Becke line. Variants of this type are found in which the outer and inner portions show other differences besides the difference in composition. Thus the inner portion may be built of zones oscillating over a small range of composition, while the outer is homogeneous (19639, 24607, 24617), or in which the outer portion shows oscillatory (23131) or continuous normal zoning (24607, 24617, 25259).

Continuous normal zoning is in accord with the theory of crystallization from a melt of two components which form solid solutions in all proportions, and we may regard it as the normal product of crystallization in an undisturbed magma, cooling slowly but not sufficiently slowly for the attainment of complete equilibrium. Discontinuous change in composition such as described above, accompanied in some cases by change in the mode of growth, must then imply some departure from these ideal conditions of crystallization. Yet the crystal, despite these anomalies, appears to be a unit; the inner portion shows no appearance of corrosion such as is described later under the heading of simple reverse zoning. It seems that we should postulate some change in physical or chemical conditions which would cause a sudden change in the composition of the material precipitated without affecting that already crystallized. Removal of the crystal to a hypothetical less calcic part of the magma does not appear to be a probable explanation. Presumably this would involve an upward movement effected against gravity by convection currents, for the sudden origin of which it would still be necessary to provide an explanation. Further, unless the transportation were very rapid there should be continuous change between the inner and outer

portions. Influx of more sodic magma may be suggested, but if the temperature remained the same, corrosion of the crystallized material should be expected to take place. A possible explanation which appears to give the required suddenness and proper direction of change in the physico-chemical conditions is that the magma, owing to relief of pressure consequent on eruption of overlying magma with which it is in hydrostatic communication, loses some of the volatile constituents. Experiment has shown that the melting-points of potassium silicates are lowered by about 50° C. by the presence of 1 % of water. Lowering of the melting-points of the alkali-felspars is possibly of the same order.[1] It may be expected, therefore, that the liquidus and solidus of the plagioclase series will be lowered, though probably not by a constant amount from end to end, by the presence of water and other volatiles. If this is the case, then sudden release of volatiles from a magma depositing a medium plagioclase will cause sudden change towards a more sodic composition in the material crystallizing out. An objection to this hypothesis is that the lowering of the solidus temperature might be sufficient to cause crystallization of the whole magma. As this has not occurred we must suppose that the amount of volatile constituents lost is quite small, and that, therefore, communication between the chamber of erupting magma and the lower chambers is very incomplete.

Simple reverse zoning.—Sections showing reverse zoning without oscillation are numerous (23073, 25757, &c.). The boundary between the zones is always sharply defined. The central portion of the crystal has, as a rule, rounded, and sometimes irregularly corroded outlines (pl. XXII, fig. 5), while either the outer zone may be idiomorphic (pl. XXII, figs. 4 and 5) or it may form a ring of fairly constant width around the inner portion (pl. XXII, fig. 3). Occasionally either the core or the border may possess a zoning not shared by the other, and the zoning of the core may be transgressed by the border zone as shown in the photograph last mentioned. In few cases can the composition of the zones be determined, but section 23996 shows a crystal cut parallel to (010) which possesses three sharply demarcated zones in which the extinction-angles against the (001) cleavage are 7° (core), 17° (intermediate zone), and 10° (border zone), corresponding to 37, 50, and 42 % An respectively.

In attempting to trace the history of such zoned felspars due

[1] Compare N. L. Bowen, The evolution of the igneous rocks. Princeton, 1928, Chap. xvi and p. 289.

attention must be paid to the existence of rounded or corroded outlines of the inner portion and to such allied features as zone truncation and differential distribution of inclusions. Some crystals, for example, show a core crowded with inclusions from which the surrounding zone is quite free (pl. XXII, fig. 4). Others show inclusions grouped along, and sometimes penetrating, the outline of the core. As a general rule there is some essential difference, such as those mentioned, between a less calcic core and a more calcic surround. It is therefore clear that in most cases of simple reverse zoning the cores are in a sense xenocrystic to the rock of which it now forms a part. This, however, does not imply that they are fragments of a previously consolidated rock detached by rising basaltic magma. They are probably early-formed crystals in a magma similar to or cognate with the rock now enclosing them. Since they are comparatively rich in albite it seems doubtful whether they are direct crystallizations from basaltic magma, and in this connexion it may be recalled that many of the lavas of the district are trachybasalts and trachyandesites in which porphyritic and groundmass felspars with low anorthite content are common. The simple reverse zoning described above may thus indicate active communication between magma chambers which contain liquids of different composition, and in some of which crystallization is in progress. The line between the zones is thus comparable with an unconformity and represents a period during which corrosion and transportation may have taken place.

Oscillatory Zoning.—Many plagioclase crystals show between crossed nicols that they are built of a large number of thin shells which can be shown by differences in extinction-angle and in refractive index to be alternately less and more calcic. The crystal is in effect built of two plagioclases which are deposited alternately. The zoning has therefore been called oscillatory. The change from one zone to another is not, however, truly oscillatory as it is not gradual but abrupt, and the zoning would be better described as alternating or rhythmic. In addition to the alternation in composition of the shells, each series of alternate shells changes in composition from centre to periphery. In some crystals the outward change is towards more albitic plagioclase, and such a zoning is here termed oscillatory-normal. On rotation between crossed nicols a wave of extinction passes from centre to margin, and under a low power the crystal seems normally zoned. In other crystals the outward change is

towards more calcic plagioclase, and the zoning is oscillatory-reverse. The two cases are shown diagrammatically in fig. 1 *a* and *b*, which have been constructed from measurements made on crystals in sections 18574 and 23996 respectively. In those figures abscissae represent distance from the centre of the crystal, and the ordinates give the extinction-angles of the zones. Horizontal lines indicate

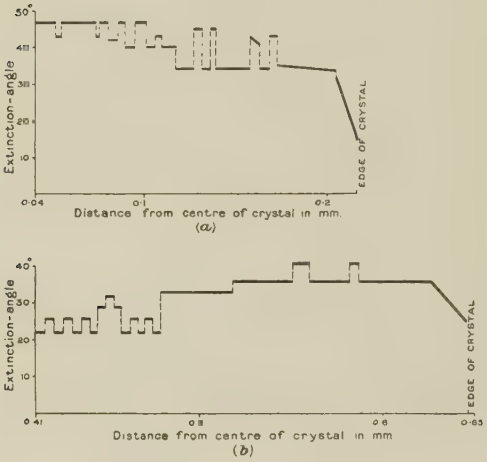

Fig. 1.

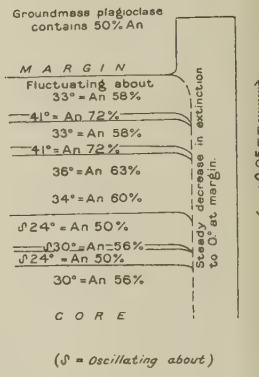

Fig. 2.

Fig. 1. · Types of oscillatory zoning in plagioclase felspar.

(*a*) The zoning though oscillatory is normal, that is, the progression of zoning is more sodic outwards. (Compare pl. xxii, fig. 1.)

(*b*) The zoning is oscillatory-reverse, that is, the progression of zoning is more calcic outwards. Approximate compositions of the zones are shown in fig. 2.

Fig. 2. Approximate composition of zones of plagioclase felspar represented in fig. 1 *b*.

constant extinction and inclined lines varying extinction (within a zone). The general change to more sodic plagioclase in fig. 1 *a* and to more calcic in fig. 1 *b* is readily seen, and it may be observed that it takes place both by change in composition and by change in relative width of the more or less calcic zones. Both crystals show the rapid marginal variation towards oligoclasic felspar which is universal in the Calciferous Sandstone basalts of Scotland. Usually it is not possible to determine the composition of the zones without special apparatus, but in the case of the crystal which is illustrated by fig. 1 *b* the section was at right angles to the bisectrix γ, and in addition showed an ill-defined multiple twinning. On the assumption that

this was on the albite-law the compositions of the zones were obtained from the curve of extinctions published by Duparc and Reinhard[1] for such orientated sections, and the variation in composition[2] is represented diagrammatically in fig. 2. The crystal represented by fig. 1 *a* is shown in pl. XXII, fig. 1. It is not a phenocryst, but a rather large groundmass crystal.

The great majority of crystals exhibiting oscillatory zoning are idiomorphic and the zones show the same crystal faces as the crystal. Specially fine examples are seen in sections 23996 and 23074, in each of which a phenocryst contains about forty idiomorphic zones (pl. XXII, figs. 2 and 6). In the latter the crystal clearly consists of a core only faintly zoned and three broad main zones which are themselves built of a number of thin shells developed most conspicuously in the direction of strongest growth. Each main zone is oscillatory-normal, but a sharp return to more calcic plagioclase is shown by the next outer main zone. The innermost main zone is, however, less calcic than the core. This crystal then has a complex zoning consisting of oscillatory-normal combined with discontinuous normal and repeated reverse zoning.

It is common to find one or more of the zones rich in inclusions. The inclusions being confined to a particular shell have clearly been trapped during growth of the shell and are not due to corrosion or permeation at a later stage in the history of the crystal. Good oscillatory zoning is found in many sections.

II. *Discussion of the origin and significance of oscillatory zoning.*

Before proceeding to the general discussion attention is drawn to the systematic investigation of the zoning in felspar with the aid of the Fedorov stage which has recently been undertaken by workers in the Mineralogical and Petrological Institute at Basel.[3] The papers

[1] L. Duparc and M. Reinhard, La détermination des plagioclases dans les coupes minces. Mém. Soc. Phys. Hist. Nat. Genève, 1924, vol. 40, p. 32. [M.A. 3-34.]

[2] According to C. Harloff (Zonal structure in plagioclases. Leidsche Geol. Mededeel., 1927, vol. 2, p. 111) it is not possible to obtain the exact percentages of anorthite in the minute zones of oscillatory-zoned plagioclase by this method, and the compositions shown in the diagram must be regarded as approximations.

[3] F. Homma, Über das Ergebnis von Messungen an zonaren Plagioklasen aus Andesiten. Schweiz. Min. Petr. Mitt., 1932, vol. 12, pp. 345–352. [M.A. 5–436.]

G. Paliuc, Untersuchungen der Plagioklase einiger tertiärer Ergussgesteine Siebenbürgens (Rumänien). Ibid., 1932, vol. 12, 423–444. [M.A. 5.]

S. Ghika-Budesti, Les plagioclases des banatites. Ibid., 1931, vol. 11, pp. 12–26. [M.A. 5–436.]

quoted contain much detailed quantitative work on the composition of the zones in oscillatory zoned crystals, and those by Homma and Paliuc show the results graphically as in fig. 1 *a* and *b*. The types to which the writer has referred as oscillatory-normal and oscillatory-reverse are conspicuous in the diagrams, but equally important is zoning in which the average composition of the less and more calcic series remains practically constant. Though many of the crystals investigated by those authors are built of homogeneous shells abruptly separated from the contiguous ones, crystals are also common in which continuous transition to more acid plagioclase is the rule within the shells. The change from the less calcic plagioclase of one shell to the more calcic plagioclase of the next shell is, however, always discontinuous. In a considerable number of crystals some of the more calcic zones are homogeneous while others are continuously zoned. Since those types are not illustrated in the rocks studied by the writer, examples are reproduced in fig. 3 from the paper by Paliuc. In a small number of the diagrams main zones which are oscillatory-normal zoned can be easily identified and the diagrams represent crystals of the type illustrated in pl. XXII, fig. 6. Those authors call attention also to evidence of corrosion between contiguous zones. In twenty crystals in which the zoning is represented diagrammatically, Paliuc observes corrosion in eight. In seven of those the corrosion has affected a shell of the more acid set; in only one has a shell of the more calcic set been attacked. It should, however, be emphasized that the contact of a calcic shell with its inner more acid neighbour is in the great majority of cases idiomorphic and shows no sign of corrosion.

Crystallization under steadily falling temperature and without complete establishment of equilibrium from a magma of two components which form a continuous series of solid solutions in all proportions results as we have seen in the formation of crystals continuously zoned from more calcic to more sodic felspar. When the same change takes place in stages represented by zones of increasingly albitic composition sharply separated from one another it has been supposed that periodic resorption has been operative.[1] In certain of the crystals under consideration the general outward change from more to less calcic plagioclase is effected by compound stages each of which involves precipitation of two very thin shells, one of more and one of less calcic composition. The alternation of such very

[1] A. Harker, Natural history of igneous rocks. London, 1909, p. 232.

thin zones (sub-zones) has been explained by Harloff as a consequence of lack of balance between the rate of diffusion and the rate of crystallization. If the rate of deposition in the region immediately surrounding the growing crystal, or shortly the *domain of crystallization*,

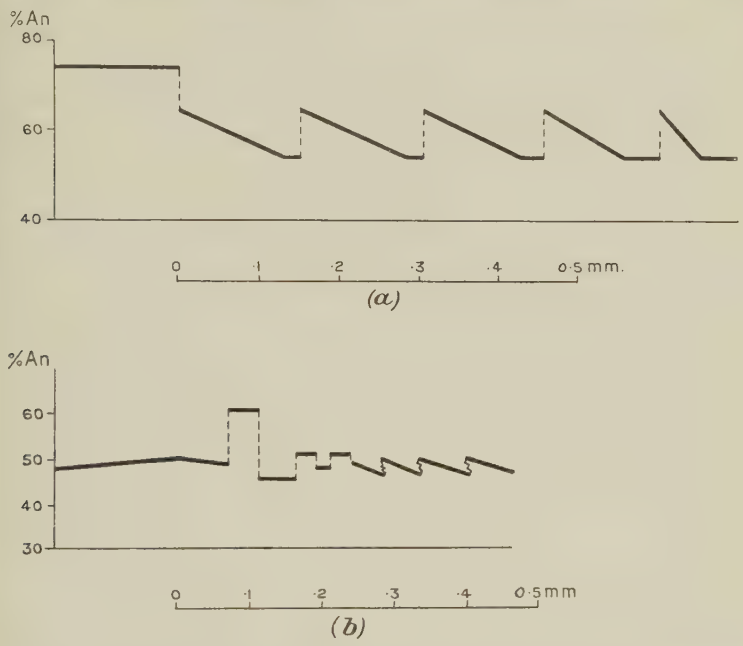

Fig. 3. Types of oscillatory zoning in plagioclase felspar.

(*a*) The change from the more to less calcic felspar is continuous, from less to more calcic felspar discontinuous.

(*b*) The crystal shows both continuous and discontinuous change to less calcic, but always discontinuous change from less to more calcic felspar. Zigzag vertical lines indicate evidence of corrosion.

There is no general progression towards either less or more calcic felspar. (After G. Paliuc, 1932.)

exceeds the rate of diffusion into this domain the composition of the residual liquor must become more albitic. According to Harloff (loc. cit., pp. 103–104):

Thus the felspar grows on, becoming more acid. Meanwhile, the rapidity of diffusion increases, because of the growing difference in concentration between the part immediately surrounding the crystal and the other parts of the liquid phase. Calcic ions, that were intended by diffusion to re-establish the former concentration in the acid part, now meet the growing crystal surface, before having succeeded in fulfilling their original intention. This causes a surplus of

calcium in the liquid phase, where it borders immediately on the crystal, resulting in the crystallization of a new sub-zone, with a composition above the average composition of the main zone, of which it forms part. The sub-zones are thus the result of a reciprocal influence of the rapidities of crystallization and of diffusion, causing the crystallization of alternating calcic and sodic zones.

The writer, while agreeing with Harloff that the alternation of minute zones indicates some rhythmic process occurring within the domain of crystallization, is unable to follow in detail the modus operandi as outlined above. On theoretical grounds it is to be expected that deposition will halt when the concentration of anorthite in the domain of crystallization is reduced, unless there is at the same time a drop in temperature. From figures given by Bowen (loc. cit., p. 46) the drop in temperature between the crystallization of $Ab_{20}An_{80}$ and $Ab_{25}An_{75}$ from a melt of plagioclase $Ab_{50}An_{50}$ and 15% of diopside is 75° C. If figures of the same order hold for temperature and composition during crystallization from a basaltic magma, Harloff's explanation of alternating more or less calcic sub-zones requires temperature oscillations of a magnitude which is very improbable. Indeed it would seem likely that temperature change within the domain of crystallization should, owing to release of heat on crystallization, be in the direction of a slight rise. If, therefore, the rate of diffusion is considerably less rapid than the rate of crystallization, deposition should cease and there is a possibility that resorption may ensue or that the crystal margin may be changed over into less calcic felspar by reaction with the surrounding more albitic liquor. The rhythm of events may thus be: (i) deposition of plagioclase with a much higher An:Ab ratio than in the magma, and concomitant concentration of albite in the liquor within the domain of crystallization; (ii) reaction of the crystal periphery with the more albitic liquor to form a less calcic plagioclase, and concurrent rise of the An:Ab ratio in the liquor both through reaction and through diffusion; (iii) deposition of calcic plagioclase once more. As the magma cools both the more and the less calcic zones will progress towards more sodic compositions.

This process of periodic resorption working under conditions of rapid crystallization and slow diffusion may be tentatively considered explanatory of the thin alternating more and less calcic shells, but it is not capable of explaining the appearance of zones more calcic than the plagioclase deposited at the beginning of crystallization. Neither can it account for the division of oscillatory-zoned crystals into main zones. For example, it may explain the thin alternating shells

represented on the left-hand portions of the graphs, fig. 1 *a* and *b*, and those of the crystal shown in pl. XXII, fig. 6. It does not, however, seem applicable to the appearance of narrow calcic zones within a broad band of less calcic plagioclase as in fig. 1 *a*, right-hand portion, and is quite incapable of explaining the consistent progression towards more calcic plagioclase shown in fig. 1 *b* and the division of the crystal, fig. 6, into the broad main zones, which at their inner wall show abrupt return to calcic plagioclase. These features of oscillatory-zoned crystals must now be considered.

The problem is in part similar to that presented by simple reverse zoning, but while, as already pointed out, certain features such as corroded and rounded zone boundaries or differential distribution of inclusions within the zones accompany simple reverse zoning, it is found that the boundaries between the zones and particularly between the main zones, in oscillatory-zoned crystals are idiomorphic and that features such as corrosion or differential distribution of inclusions are more often absent than present. Therefore it seems probable that there has been no such hiatus in the growth of the crystal as has been postulated in the history of simple reverse zoned crystals. We may at this point review some hypotheses relating to the production of oscillatory-reverse zoning.

Reversal of the normal order of zoning in plagioclase felspar has been explained by Harker (loc. cit., p. 233) and by Iddings[1] as a consequence of supersaturation. According to this hypothesis crystallization does not begin until some time after the liquidus temperature has been passed and plagioclase more acid than would normally be deposited from a melt of the particular composition separates out. In virtue of the heat liberated by rapid crystallization the temperature rises permitting more calcic plagioclase to separate until temperature and crystal and magma compositions reach the equilibrium values, whereupon crystallization follows the normal course. It is possible on this hypothesis to have reverse zoning followed by normal zoning, but it does not seem probable that the *repeated* alternation of reverse and normal zoning exhibited by oscillatory-zoned crystals can be thus accounted for, since supersaturation can occur only once. Fenner[2] and Bowen (loc. cit., pp. 274–275) have both discussed the phenomenon of oscillatory zoning with particular regard to its

[1] J. P. Iddings, Igneous rocks. New York, 1909, vol. 1, p. 177.

[2] C. N. Fenner, The Katmai magmatic province. Journ. Geol. Chicago, 1926, vol. 34, pp. 700–703.

significance as an indicator of events in the history of the magma. Neither of these writers draws the distinction between main zones and the thin shell alternations, and Bowen alone makes the attempt to trace in detail the causes which lead to the rhythmic deposition of more and less calcic plagioclase. He considers that oscillatory zoning may 'find a probable explanation in several periods of sinking with intermittent surging forward of the mass'. During each period of sinking the crystal will reach portions of the magma which, being at a higher temperature, are able to deposit plagioclase more calcic than accrued to the crystal at a higher level. During suspension in this hotter region the surface layer of the crystal reacts with the magma and is either made over to more calcic plagioclase or taken into solution. In the latter event calcic plagioclase is deposited later when the temperature has fallen to the required value. Bowen conceives that in this way reverse zoning may arise, and, if the whole body is then carried to higher (cooler) levels, a new cycle of cooling and sinking will cause deposition of a second set of less and more calcic zones, and so on. As Bowen points out there should be on this hypothesis a general outward tendency to more sodic zones; the hypothesis may therefore explain the oscillatory-normal type of zoning in some cases, though it seems an impossibly intricate way of explaining the oscillatory-normal zoning of the groundmass crystal shown in pl. XXII, fig. 1, and in text-fig. 1 *a*.

Fenner suggests three explanations. First, oscillatory zoning is a reflection of changes of composition of the magma brought about by external causes; second, the crystals may settle into a more calcic portion of the magma and be carried upward again into more sodic layers; or lastly, the form of combination or relative solubilities of the constituents of the magma may be changed by escape of volatiles, perhaps during an eruption, to such a degree that the ratio of albite to anorthite deposited is considerably affected.

Homma (loc. cit., pp. 350–351) favours the second explanation suggested by Fenner and considers that the movement of the crystal is due to convection currents in the magma chamber and is aided by escape of volatiles which, bubbling upwards, help to float the crystals to the top of the chamber whence they descend under gravity and in the downward convection stream. Harloff (loc. cit., p. 104) suggests that sudden escape of volatile constituents is the cause of rapid crystallization of zones of a composition different from those already deposited.

The various hypotheses invoke recurrence of the following incidents separately or in some combination:

(*a*) Movement of crystals in the magma, whether by gravitative settling or by convection currents.

(*b*) Movement of the magma as a whole into a region where different conditions of temperature and pressure prevail.

(*c*) Irruption of additional magma into the crystallizing liquid.

(*d*) Loss of volatile constituents.

All of those incidents must be regarded as probable events in magma which is awaiting eruption. In judging which or which combination of them is probably effective in producing oscillatory zoning we must take into account the number of recurrences. Thus during the growth of a crystal with forty zones there must be twenty recurrences. It seems to the writer that the hypothesis put forward on p. 550 which involves rhythmic changes in anorthite concentration around a growing crystal is more probable than hypotheses based on a large number of recurrences of external influences, and that this hypothesis in combination with one involving a few recurrences of external influences is capable of explaining the phenomena of oscillatory zoning. The external influence which is most likely to affect magma at the roots of a volcano is relief of pressure consequent on eruption. Relief of pressure will result in loss of volatiles to an extent depending on the openness of communication between magma chamber and the throat of the volcano. So far as loss of volatiles can directly affect the nature of the plagioclase deposited the difference must lie towards the more sodic end. More calcic plagioclase cannot separate out as the direct result of loss of volatile components. Relief of pressure causing streaming upward of volatiles may, as suggested by Homma, aid circulation of crystals within the magma chamber. Whether movement of crystals from higher to lower levels in the chamber can achieve the observed difference in composition of plagioclase in contiguous zones the writer has been unable to decide, as too many unknown factors are involved, principally the thermal gradient, which must be small if convection currents are operative, the degree of homogeneity of the magma, the thickness of the magma chamber. Relief of pressure consequent on eruption must, however, find an echo in the tendency of magma at lower levels to ascend to higher. It is therefore possible and probable that ascending hot magma will be erupted into higher chambers in which crystals are forming. It is by periodic accession of such hot magma that the

writer would explain the abrupt recurrence of the more calcic zones which form the inner shells of the main zones of oscillatory-zoned crystals, the abrupt appearance of thin highly calcic shells, and the phenomenon of outer zones more calcic than the core.

Summary.—The paper describes various types of zoning in plagioclase felspar in the Calciferous Sandstone basalt lavas in one district of Scotland. The zoning is classified as (*a*) normal, (*b*) simple reverse, (*c*) oscillatory. Simple reverse zoning is associated with other differences in the zones which point to important time intervals between the growth of the zones. Oscillatory zoning is classified as oscillatory-normal and oscillatory-reverse and attention is drawn to the occurrence of oscillatory-zoned crystals which show no general tendency towards either more calcic or more sodic composition. Distinction is drawn between the main zones and the thin shells of alternately more and less calcic composition within the main zone. The alternating composition of the thin shells is possibly the result of lack of balance between rate of growth of the crystal and rate of diffusion from the surrounding magma. Recurrence of calcic plagioclase in the inner part of main zones is explained as the result of irruption of hot magma into the crystallizing liquid, probably consequent on eruption of lava at higher levels.

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Explanation of Plate XXII.

Photomicrographs of plagioclase crystals in Scottish basalts.

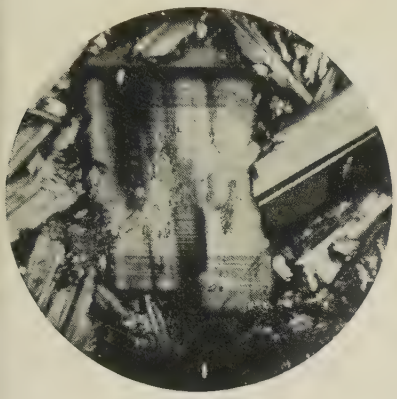
Fig. 1. Slice[1] 18574. An oscillatory-normal zoned crystal of plagioclase of groundmass size. There is a general progression outwards towards more sodic plagioclase. Compare text-fig. 1 *a*. Crossed nicols. ×76.

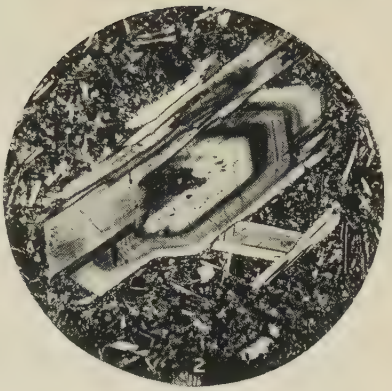
Fig. 2. Slice 23996. Oscillatory-zoned crystal showing main zones with general progression towards more sodic plagioclase within each main zone. The most calcic zones are in the extinction position. Crossed nicols. ×10.

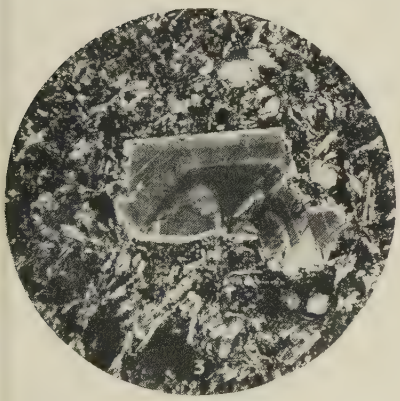
Fig. 3. Slice 23073. An oscillatory-zoned crystal has been corroded and more calcic plagioclase has been deposited after the corrosion as a narrow rim which truncates the zoning of the core. Exemplifies simple reverse zoning. Crossed nicols. ×25.

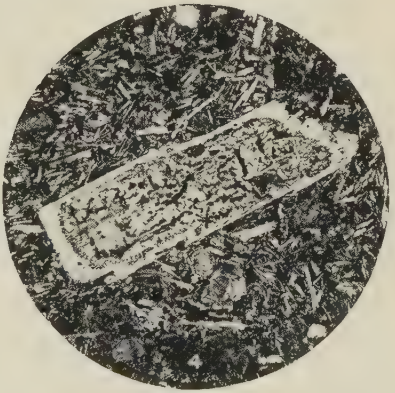
Fig. 4. Slice 25757. Exemplifies essential difference between core and outer shell in a simple reverse zoned crystal. The core is crammed with inclusions of ore, pyroxene, and serpentinous material and has a roundish outline. The outer shell, which is of more calcic plagioclase, is free of inclusions. Crossed nicols. ×18.

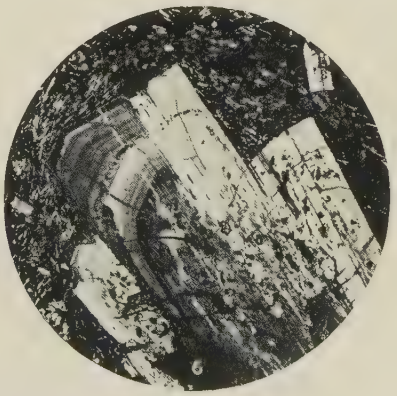
[1] Registered rock slices in the Geological Survey collection of Scottish rocks.











J. Phemister: Zoning in Plagioclase Felspar.

FIG. 5. Slice 23996. Exemplifies simple reverse zoning. The less calcic core has an outline rounded by corrosion. The more calcic plagioclase surrounding the core is idiomorphic and is normally zoned at the periphery. Crossed nicols. ×34.

FIG. 6. Slice 23074. The crystal exhibits very well the division into main zones which are composed of thin shells of alternately more and less calcic composition, and which show a general outward progression towards more sodic plagioclase, an abrupt return to calcic plagioclase being made in the next outer main zone. Inclusions of pyroxene, ore, and serpentine are confined to (*a*) the core and (*b*) the most calcic zone of the largest main zone. In this crystal the core has the most calcic composition. Crossed nicols. ×18.

Studies on the zeolites. Part VII.[1] *'Clinoptilolite', a silica-rich variety of heulandite.*

By Max H. Hey, M.A., B.Sc., and F. A. Bannister, M.A.
Assistant-Keepers in the Mineral Department of the British Museum of Natural History.

[Read January 25, 1934.]

In 1890, L. V. Pirsson[2] described under the name of mordenite a crystalline mineral, isomorphous with heulandite, occurring in a highly weathered amygdaloidal basalt in the Hoodoo Mts., Wyoming. His analysis (1, table I) showed that the mineral had a composition near that of the original mordenite of H. How (1864) and his assumption that it represented a platy-crystalline phase of that normally fibrous mineral was generally accepted.

More recently, T. L. Walker and A. L. Parsons[3] have suggested the identity of How's fibrous mordenite with ptilolite, which is known as well-developed crystals crystallographically quite different from those of Pirsson's mineral. The latter, in this case, cannot be mordenite. W. T. Schaller,[4] who differentiates between ptilolite and mordenite, regards Pirsson's material as an independent species; neglecting its obvious affinities to heulandite, noticed by Pirsson, he proposes for it the very inappropriate name of clinoptilolite, and regards it as having the same fixed composition as ptilolite, namely $(Ca,Na_2,K_2)O.Al_2O_3.10SiO_2.7H_2O$.

Recently M. N. Bramlette and E. Posnjak[5] have described a zeolite from Dome, Arizona, which gives analytical figures near Pirsson's material, but distinctly lower in silica. Its optical properties agree with those of Pirsson's material, as determined by Pirsson and

[1] Part VI. Edingtonite. Min. Mag., 1934, vol. 23, p. 483.

[2] L. V. Pirsson, Amer. Journ. Sci., 1890, ser. 3, vol. 40, p. 232.

[3] T. L. Walker and A. L. Parsons, Univ. Toronto Studies, Geol. Ser., 1922, no. 12, p. 61. [M.A. 2-55.]

[4] W. T. Schaller, Amer. Min., 1932, vol. 17, p. 128; also in abstract in Amer. Min., 1923, vol. 8, p. 93, and quoted in C. S. Ross and E. V. Shannon, Proc. U.S. Nat. Mus., 1925, vol. 64, p. 3. [M.A. 5-147, 2-301; Min. Mag. 20-450.]

[5] M. N. Bramlette and E. Posnjak, Amer. Min., 1933, vol. 18, p. 167. [M.A. 5-357.]

amplified by E. S. Larsen. Bramlette and Posnjak therefore class their material as clinoptilolite, but they observe that as they were unable to distinguish between Debyeograms of their material, Pirsson's material, and heulandite it will be necessary to consider further the relation between clinoptilolite and heulandite. This the present authors have done, and conclude that there can be no doubt that 'clinoptilolite' is merely a high-silica heulandite. The identification is based mainly on an X-ray study of single crystals.

No specimen of 'clinoptilolite' was available in the British Museum collection, but Prof. W. E. Ford very kindly loaned us the type specimen, no. 5268, from the Brush collection of the Sheffield Scientific School, Yale University, U.S.A. A small crystal detached from this was examined optically with results in close agreement[1] with Larsen's, then mounted and an X-ray rotation photograph taken about the a-axis. This proved to be completely identical with a photograph of a heulandite crystal about the a-axis. Long exposure photographs were also taken with iron radiation. The greater resolution thus obtained failed, however, to reveal any differences between heulandite and 'clinoptilolite'.

Now long exposure rotation photographs of small single crystals of natrolite, mesolite, and scolecite, three zeolites possessing very closely related crystal structures, are easily distinguished whether copper or iron radiation be used.[2] We therefore conclude that 'clinoptilolite' and heulandite must be members of an isomorphous series.

If they were independent species there should be differences in the optical properties greater than can be accounted for by the difference in composition. But the difference in the optical properties of ordinary heulandite and 'clinoptilolite', though considerable, is just about what one may expect from the effect of an increase in silica on the optics of thomsonite,[3] namely a decrease of about 0·01 in the refractive index for replacement of CaAl by NaSi in a unit cell of 80 oxygen atoms, together with a marked decrease in the greatest refractive index relatively to the other two[4] (actually the decrease is enough to change the optic sign).

[1] The present authors find n 1·48 approx., birefringence low, extinction undulatory, $Bx_o(?) \perp b$ (010), probably optically negative.

[2] Part V of this series, Min. Mag., 1933, vol. 23, p. 421; compare W. H. Taylor, Zeits. Krist., 1933, vol. 84, p. 373. [M.A. 5-354.]

[3] Part II of this series, Min. Mag., 1932, vol. 23, p. 51.

[4] It appears probable from the data so far available that in many zeolites the birefringence is largely due to polarization by the charged aluminium atoms, and

In chemical composition, both Pirsson's material and Bramlette and Posnjak's agree with silica-rich heulandite.[1] Heulandite shows marked variations in composition, the silica content ranging from 53 to 61 %; the 'clinoptilolites' show 66 % and 64 % silica in the two published analyses. The oxygen content for both heulandite[2] and 'clinoptilolite' is 72 atoms per unit cell, and the two analyses, recalculated into atomic proportions on this basis, are reproduced in table I.

TABLE I. Chemical composition (atomic ratios per 72 oxygen atoms) and optical properties of high-silica heulandites ('clinoptilolites').

	1.	2.
Si	30·04	29·26
Al	5·96	6·84
Ca	0·54	1·18
Na	2·00	3·48
K	2·06	0·78
H_2O	20·34	21·64
Ca+Na+K	5·00	5·44
Sp. gr.	2·14	—
Oxygen atoms per unit cell ...	73·1*	—

1. Hoodoo Mts., Wyoming; L. V. Pirsson, 1890. Ax. pl. and $a \perp b(010)$, $\gamma : a = 15°$, birefringence low (Pirsson). α 1·476, γ 1·479, 2V small, negative, $\beta \perp b$ (010), extinction on b 34° (E. S. Larsen, determined on original material, quoted by W. T. Schaller, loc. cit.).

2. Dome, Arizona; M. N. Bramlette and E. Posnjak, 1933. n 1·480, birefringence low, extinction undulatory, $\gamma \perp b$ (010), 2V large, negative (?).

* Taking Wyart's figures for heulandite (loc. cit.) for the cell sides; this procedure is justified by the complete identity of rotation photographs of heulandite and 'clinoptilolite'.

The unit cell formula of heulandite appears from the data so far available to be essentially $Na_xCa_yAl_{x+2y}Si_{36-(x+2y)}O_{72}\cdot 24H_2O$, where $(x+y)$, the number of cations per unit cell, is variable, ranging from

their replacement by silicon appears as a rule to decrease the birefringence very markedly.

[1] W. T. Schaller, as quoted by Bramlette and Posnjak, considers that the differences in chemical composition between the Arizona and Wyoming material are unimportant. In the present authors' opinion, the differences are well outside the probable experimental error; moreover, Schaller does not give any grounds for his statement that the Arizona material contained 5 % of clay. The analysis itself affords no internal evidence of impurity; and even 5 % of clay would not account for the differences.

[2] For the unit cell contents of heulandite, compare J. Wyart, Compt. Rend. Acad. Sci. Paris, 1930, vol. 190, p. 1564. [M.A. **4**-369.] The figures there given are half the unit cell contents, the end-centred cell containing two 'structural units'.

4 to 6, and $(x+2y)$, the number of aluminium atoms per unit cell, ranges from 8 to 10 in most heulandites. In the 'clinoptilolites', the aluminium content falls as low as 6 atoms per unit cell, while the cation content is within the above range of 4–6 atoms. The water content, in both 'clinoptilolites' and ordinary heulandite, generally falls considerably below 24 molecules per unit cell; this is probably due to the high vapour-pressure of the quasi-saturated zeolite at room-temperatures. Similar behaviour has been observed in the case of edingtonite.

Since the minerals examined by Pirsson and by Bramlette and Posnjak are essentially high-silica heulandites, without any simple relation to mordenite or ptilolite,[1] the name 'clinoptilolite' is unsuitable and should not be used.

[1] X-ray photographs of mordenite and ptilolite are quite different from those of heulandite, and appear to be identical; the name mordenite has priority.

On the advantages of the face-adjustment for two-circle goniometry.

By Max H. Hey, M.A., B.Sc.
Assistant-Keeper in the Mineral Department of the British Museum of Natural History.

[Read March 15, 1934.]

IN two-circle goniometry as usually practised, the zone-adjustment is almost invariably used. It would be difficult to discover the reasons which have led to this unfortunate neglect of the face-adjustment; actually the face-adjustment has all the advantages of the zone-adjustment without its defects.

In the orthorhombic and higher systems, the zone-adjustment as generally practised (adjustment of the zone *ab* [001]) is identical with a face-adjustment of *c* (001), and there is therefore no distinction between the two methods; it is only necessary, therefore, to consider the monoclinic and anorthic systems.

The principal advantages which two-circle goniometry, using the zone-adjustment, can claim over single-circle methods are: reduced handling of the crystal; increased speed of measurement; that an accurate projection is quickly and easily prepared, facilitating indexing and the detection of possible symmetry obscured by a distorted habit; and the possibility, by using the methods devised by V. Goldschmidt and based on the gnomonic projection, of using the whole of the measured angles in the computation of the elements. An advantage frequently quoted, that a complete table of angles is more concise than a complete single-circle table of angles, is, in the author's opinion, of no importance. The only proper functions of a table of angles in an original paper are to record the actual measurements[1] and to compare them with the calculated values, and with the corresponding angles of isomorphous substances. Formerly, a table of angles was regarded partly as a collection of determinative data, but the introduction of a rational determinative system based

[1] This primary function is not fulfilled by the tables of angles sometimes given, containing calculated angles only.

on crystal morphology[1] by T. V. Barker renders this function obsolete (except in mineralogy, where there is generally a strong suspicion as to the identity of a crystal before the actual determination is begun), so that a complete table of angles is no longer a desideratum in an original description.

It will be obvious that the advantages of reduced handling and increased speed of measurement remain with two-circle goniometry whatever form of adjustment is used—indeed, the crystal may even be measured without adjustment, a useful facility in the case of highly deliquescent or very unstable substances. The face-adjustment, therefore, retains these advantages. The objections that are generally urged against it are that the preparation of a projection is not so simple as with the zone-adjustment, and that computation is not so straightforward. Both objections are quite fallacious.

In anorthic crystals, with the zone-adjustment (the zone adjusted being *ab* [001]), the method of projection on a plane normal to the adjusted zone is illustrated by fig. 1; since each face-pole has its own ϕ and ρ values, it is necessary in projecting each pole to draw a line OP at an angle ϕ with OP_0 (for which $\phi = 0°$), and measure off $OP = r.\tan \rho$, where r is the radius of projection.

It is usually stated that an equally simple method of projection is not available for the face-adjustment, and if the face adjusted is a terminal face, as *c* (001), this is true; but if the face adjusted lies in the prism zone, say *b* (010), the method of projection is quite as simple and often even quicker. Instead of separate ϕ and ρ values for each face, we shall have, since the faces usually all lie in relatively few zones through *b* (010), a few interzonal angles at *b*, and an interfacial angle from *b* to each other face. To project on a plane normal to zone *ab* [001], a line OM (fig. 2) is drawn to represent the trace of *b* (010); normal to this is the gnomonic *b*-axis, OB. Lay off along OM distances $OR = r.\cot \Phi$, where Φ is the interzonal angle $[ab] : [bPQ \ldots]$ and, in the opposite direction, $OT = r.\tan \Phi/2$, and draw RPQ perpendicular to OM. Then RPQ is the gnomonic zone-line $[bPQ \ldots]$, and T is the stereographic pole of this zone. To project all the faces in the zone, it is only necessary to draw lines TP, TQ, &c., making with RT angles $90° - bP$, $90° - bQ$, &c. (bP, bQ being the inter-

[1] The author would add a fifth independent sub-division of crystallography to the four given by A. F. Rogers (Amer. Min. 1933, vol. 18, p. 538); determinative crystallography differs sufficiently in its aims and methods from pure morphology or from structural crystallography to form a separate sub-division.

facial angles between $b(010)$ and the faces P, Q, &c.), to cut RPQ at the points P, Q, &c., which are then the gnomonic poles required.[1] The same proceeding is followed with each other zone through $b(010)$, and the projection is quickly and accurately made. The distance of the 'angle-point', T, from O cannot exceed r, the radius of projection. If the faces are numerous and concentrated in a few zones through $b(010)$, the advantages of the method become most evident.

With a monoclinic substance, face-adjustment of $b(010)$ is identical with zone-adjustment of ac [010], and much preferable to the adjustment of any other face or zone-axis.[2] If the crystal is to be projected on a plane perpendicular to the zone ab [001], the above procedure serves, while a projection on the face $b(010)$ is readily made by the usual method.[3]

Turning now to the matter of computation, it will readily be seen that with $b(010)$ in face-adjustment, x and y, the Goldschmidt rectangular co-ordinates[4] of a face-pole F in the gnomonic projection are: $x = \cot[ab] : [bF]\,(= \cot \Phi)$, and $y = \cot bF.\ \mathrm{cosec}\,[ab] : [bF]$ $(= \cot bF.\ \mathrm{cosec}\,\Phi)$. Hence the normal Goldschmidt method of computation can be used quite straightforwardly.

[1] The formal proof of this construction is simple. Let OB extend to infinity, to meet RPQ in B, which will then be the gnomonic projection of $b(010)$. Draw PY parallel to TR to cut OB in Y. Then BPY is the gnomonic projection of a right-angled spherical triangle, the right angle being at Y. And the angle YBP of this triangle $= 90° - [ab] : [bP] = 90° - \Phi$. Hence $\cot BY = \cot bP.\ \mathrm{cosec}\,\Phi$. But in the gnomonic projection, $RP - OY = \cot BY$. And $RP = RT.\ \cot bP$ by construction. Hence if $RT = \mathrm{cosec}\,\Phi$, the construction is correct. Now by construction, $RT = \cot \Phi + \tan \tfrac{1}{2}\Phi = \mathrm{cosec}\,\Phi\ (\cos \Phi + \sin \Phi\,.\,\tan \tfrac{1}{2}\Phi) = \mathrm{cosec}\,\Phi$ $(1 - 2\sin^2 \tfrac{1}{2}\Phi + 2 \sin \tfrac{1}{2}\Phi\,.\,\cos \tfrac{1}{2}\Phi\,.\,\tan \tfrac{1}{2}\Phi) = \mathrm{cosec}\,\Phi$.

[2] The face $b(010)$ can almost always be adjusted, even if it is not developed. Thus the zone ac [010] may be adjusted, which comes to the same thing, since the face b is perpendicular to this zone-axis; or the zone ab [001], or any other zone containing $b(010)$, may be adjusted parallel to the axis of the horizontal circle, the zone measured, and the position of $b(010)$ calculated. Then any face is brought into the reflecting position, the horizontal circle turned through the angle which the normal to $b(010)$ has been found to make with the axis of the vertical circle, and the face brought back into the reflecting position by means of the crystal-adjusting segments. With the three-circle goniometer, this adjustment is made with the greatest ease by means of the third circle.

[3] The principal advantage of projection on $b(010)$ lies in the assistance given in selecting the most suitable axes. Cf. T. V. Barker, Systematic crystallography. London, 1930, p. 44.

[4] Projection is assumed to be on a plane perpendicular to the zone ab, and the y-axis is parallel to the zone-line bc. The radius of projection is taken as unity. With the zone ab in zone-adjustment, $x = \tan \rho\,.\,\sin \phi$, $y = \tan \rho\,.\,\cos \phi$.

It is thus evident that the face-adjustment retains all the advantages over single-circle goniometry possessed by the zone-adjustment. And it possesses several distinct advantages over the zone-adjustment. Not the least is the fact that the measured angles are all interfacial or interzonal angles, while with the zone-adjustment, the measured angles are of no direct crystallographic significance, being neither interfacial nor interzonal angles. Further, the measurement proceeds

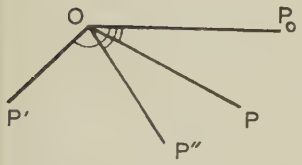


Fig. 1.

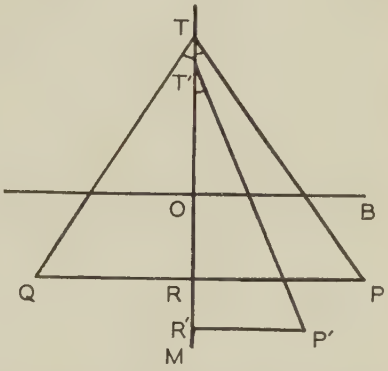


Fig. 2.

Fig. 1. The preparation of a projection, after measurement with the zone-adjustment, on a plane perpendicular to the adjusted zone. $OP = r \cdot \tan \rho$, angle $P_0OP = \phi$.

Fig. 2. The preparation of a projection after measurement with the face-adjustment, on a plane perpendicular to the adjusted face, $b(010)$. Radius of projection 2·5 cm. $OR = r \cdot \cot [bP] : [ba]$, $OT = r \cdot \tan \frac{1}{2} [bP] : [ba]$, angle $OTP = 90° - bP$.

on zonal lines, one advantage of which is immediately apparent in that the theoretically equal interzonal angles (Φ-angles) of all faces in any zone through $b(010)$ can be averaged directly without computation.

A less apparent advantage of the zonal course of measurement when the face-adjustment is used lies in the fact that adjustment can be made more truly, though this statement may at first sight appear open to some doubt. When the zone-adjustment is used, the faces in the adjusted zone all have $\rho = 90°$, and one is arbitrarily selected as reference-face, with $\phi = 90°$. Naturally, there will be a certain error in the determination of the actual position of this face, and hence a process of calculation from the other measured angles is necessary to correct this error (cf. L. Borgström and V. Goldschmidt, Zeits. Kryst. Min., 1905, vol. 41, p. 73, or A. L. Parsons, Amer.

Min., 1920, vol. 5, pp. 190, 198). On the other hand, no correction of the ρ values is possible, nor should such a correction be necessary, seeing that in actual practice $\rho = 90°$ will be the average reading for all the prism faces; the adjustment will have been made so that on rotating the vertical circle the departures from the vertical cross-wire of the signals from the several faces of the zone *ab* [001] as they pass across the field of view are evenly distributed—the departures to the left balance the departures to the right, after full allowance has been made for the perfection of the various reflections.

When the face-adjustment is employed, it is usual to consider that adjustment is achieved when the signal reflection from the chosen face does not move appreciably as the vertical circle is rotated. If this means of adjustment, depending solely on one face, is used, then indeed the face-adjustment is less accurate than the zone-adjustment.

But when a face has been truly adjusted, then it will be possible by rotating the vertical circle to bring every zone through that face into adjustment. Hence the correct and accurate method of making the face-adjustment is, first to adjust until the signal image from the selected face does not move as the vertical circle is rotated. Next each of the several zones [1] through the adjusted face is brought into the plane of the horizontal circle in turn; then on rotating the horizontal circle, the signal images from each face in a given zone should pass across the field of view at the same level. Any maladjustment will be apparent and can be corrected and the calculation of a correction such as is needed for the zone-adjustment is avoided. When correctly adjusted, the movement of the vertical circle should bring each zone in turn into accurate adjustment. In this way, any departure of the selected face from its true position, or any diffuseness in the signal image it gives, is eliminated. Sometimes it may prove possible to adjust a face which is not actually developed. Indeed, it would be theoretically possible, though hardly practicable (except with the three-circle goniometer, where it is quite feasible), to bring into face-adjustment the possible face lying at the intersection of any two developed zones of a crystal.

It may be noted that when the face-adjustment is made in the above manner, we abandon the direct attempt to bring the face-normal into coincidence with the axis of the vertical circle, which

[1] It is necessary that a zone shall contain at least two faces other than the face selected for adjustment, if it is to serve as a test of the accuracy of adjustment.

cannot always be done with any great accuracy owing to vicinal development, diffuse reflections, &c.; instead, the same end is attained by bringing into coincidence with the plane of the vertical circle the axes of all sufficiently developed zones through the selected face.

The advantages of the face-adjustment over the zone-adjustment may not be so great as the advantages both can show over single-circle goniometry, but the two points above noted are of some importance. That the measured angles are all either interfacial or interzonal renders the special symbols ϕ and ρ superfluous, and the table of angles can be given in the form of interfacial angles $bF = (010) : (hkl)$ and interzonal angles $ab\,[001] : bF\,[l0\bar{h}]$. It is usual to make a projection on a plane perpendicular to the zone-axis $ab\,[001]$; if this is to be done, measurement with any face in the zone $ab\,[001]$ adjusted will give results from which a projection can readily and easily be prepared, but computation is greatly simplified if the adjusted face is [1] $a\,(100)$ or $b\,(010)$. If the above method of effecting the adjustment is employed, the face need not give particularly good reflections. Alternatively, any face may be adjusted, regarded temporarily as $b\,(010)$, a projection made and indexing and computation carried out. A 'correct' setting can then be sought on determinative or structural lines, or to correspond with some isomorphous compound, and the indices transformed and the elements for the new setting computed without difficulty. There is not the slightest need to re-compute the measured angles to correspond to a conventional selection of adjusted face for the new setting, for, as emphasized above, the primary function of a table of angles in an original paper is merely to record the actual measured values, and, if desired, to show their departure from a set of rigorously consistent values.

[1] The face $c\,(001)$ can very well be adjusted, provided projection is made on a plane normal to one of the zone axes $ac\,[010]$ or $bc\,[100]$.

Berthierite from Kisbánya, Carpathians.[1]

By Dr. Victor Zsivny and Dr. László Zombory,
Magyar Nemzeti Múzeum (Hungarian National Museum), Budapest.

[Read June 7, 1934.]

THE mineral berthierite has hitherto been known from two localities in the region of the Carpathian Mountains. It was first recorded by A. Löwe [2] in 1847 from Aranyidka [3] in the Hungarian comitat Abauj-Torna, where it occurred ' massive and disseminated, columnar and fibrous, with jamesonite and stibnite '.[4] Much later, about 1908, J. Krenner [5] recognized it from Felsőbánya [6] in the Hungarian comitat Szatmár, but his paper describing it, which was read before the Hungarian Academy of Sciences on October 19, 1908, was not published until after his death. Here the mineral occurred as parallel and radiating aggregates of deeply striated grey fibres, which are often intimately intergrown with stibnite. Other associated minerals are needles of mispickel and small plates of baryte.

The third occurrence of berthierite in this region, to be now described, is at Kisbánya [7] in the Hungarian comitat Szatmár. The material was sent for determination to the Hungarian National Museum by Mr. Gyula Kupás of Nagybánya (= Baia Mare).

[1] Read before the Hungarian Academy of Sciences, Class III (Natural Sciences), on January 15, 1934.

[2] A. Löwe, Ber. Mitt. Freunden d. Naturwiss. Wien (Haidinger), 1847, vol. 1 (for 1846), pp. 62–64.

[3] Now Zlatá Ida in župa (county) Košická, Slovakia.

[4] E. von Fellenberg, Die Mineralien der ungarischen und einiger siebenbürgischen Erzlagerstätten. Gangstudien (B. von Cotta and H. Müller), 1862, vol. 4, p. 126; also in B. von Cotta and E. von Fellenberg, Die Erzlagerstätten Ungarns und Siebenbürgens. Freiberg, 1862, p. 126.

[5] J. Krenner, Berthierit Felsőbányáról. Math. és Természettud. Értesítő, 1928, vol. 45, p. 13 (Hung.), p. 14 (Germ. résumé); German also in Centr. Min., Abt. A, 1928, pp. 270–271. [Min. Abstr., vol. 4, p. 8.]

[6] Now Baia Sprie in judeţ (district) Satu Mare, Romania.

[7] Kisbánya, meaning little mine; now Chiuzbaia, judeţ Satu Mare, Romania. Another well-known mineral locality named Kisbánya (= Járabánya or Jarabánya) is in comitat Torda-Aranyos, Transylvania (now Băişoara, judeţ Turda, Romania).

Here needles of berthierite occur singly or as parallel or irregular aggregates grown on the inside of carbonate crusts; also as brushes up to 6 cm. long, with rounded surfaces and consisting of slightly divergent groups of needles growing freely in cavities in the carbonate crusts. Rosettes of stibnite on the inside of these crusts are partly covered with berthierite needles.

The needles of berthierite are dark grey or brownish with a bright metallic lustre, but the colour on a fresh fracture is always dark grey. They are striated parallel to their length, and they break very easily across this direction.

The associated carbonates are of various kinds: probably two varieties of Ca-Mg carbonate with Fe and very little Mn, one of them crystallizing as $(10\bar{1}1)$ rhombohedra; two varieties of calcite with Fe, Mn, and Mg, one as $(01\bar{1}2)$ rhombohedra; chalybite with Ca, Mg, and Mn, as $(01\bar{1}2)$ rhombohedra; and finally, a Fe-Ca carbonate with Mg and Mn. The associated stibnite contains traces of iron and forms rosettes of crystals with bright faces.

Although the presence of stibnite amongst the needles of berthierite was not evident to the unaided eye, nevertheless it was necessary to be assured that the material collected for chemical analysis and for the determination of the specific gravity was entirely free from intergrown stibnite. For this purpose the material was treated with a solution of potassium hydroxide, when only very few needles turned red, indicating the presence of but little stibnite. This was then removed by treatment with an 8·1 % solution of KHS according to the method of J. Loczka.[1]

The material used for analysis was collected from the larger brushes. The specific gravity determined on 0·2068 gram in the small pyknometer of Winkler[2] using carbon tetrachloride is d_4^{20} 4·652.

Qualitative tests showed the presence of antimony, iron, and sulphur as the main constituents, with a trace of manganese. For the quantitative analysis the finely powdered mineral was dried at 100° C. A quantity (0·6376 gram) was mixed with four times its weight of $KClO_3$ and dissolved in HCl (sp. gr. 1·12) in the presence of tartaric acid. The antimony was precipitated as sulphide and weighed as Sb_2O_4. Iron was precipitated from the filtrate as sulphide and weighed as Fe_2O_3 after reprecipitation with ammonia. Sulphur was

[1] J. Loczka, Zeits. Kryst. Min., 1903, vol. 37, p. 383.

[2] L. W. Winkler, Ausgewählte Untersuchungsverfahren für das chemische Laboratorium. Die chemische Analyse, vol. 29, Stuttgart, 1931, p. 8.

estimated as $BaSO_4$ in an aliquot portion of the original solution, the small amount of sulphur which separated during the solution of the mineral being added to this, giving 29·40 %. A second determination of sulphur was made on a separate portion (0·4228 gram) by fusing the mineral with Na_2CO_3 and KNO_3 in a nickel crucible according to the method of Fresenius, giving 29·52 %.

The results of this analysis are given under I. Under II are the percentages reduced to 100 % after deducting the insoluble portion, showing a close agreement with the values calculated for the formula $FeS.Sb_2S_3$.

	I.	II.	Atomic ratios.	Calculated for $FeS.Sb_2S_3$.
S	29·46	29·78	4·000	29·99
Sb ...	56·06	56·65	2·009	56·95
Fe ...	13·43	13·57	1·049	13·06
Mn ...	trace	—	—	—
Insol. ...	0·33	—	—	—
	99·28	100·00		100·00

The following table shows a remarkable difference between the specific gravity of berthierite from Kisbánya and Felsőbánya and that from some other localities; the two values being about 4·6 and 4·0 respectively, although the chemical composition is essentially the same in each. The higher value [near that of stibnite 4·5 – 4·6] is no doubt the correct one. Nos. 3 and 5 are old determinations, and in no. 4, 19·76 and 23·31 % of quartz were deducted from the results of the analysis for which no allowance was made in the specific gravity.

	1.	2.	3.	4.		5.
Sp. gr. ...	4·652	4·622	4·043	3·89—3·91		4·062
S	29·46	29·28	29·27	29·18	30·20	29·12
Sb ...	56·06	55·96	57·88	57·44	55·40	56·61
Fe ...	13·43	12·61	12·85	13·38	14·40	10·09
Mn ...	trace	0·31	—	—	—	3·56
Insol. ...	0·33	0·05	—	—	—	—
	99·28	99·45	100·00	100·00	100·00	99·38

1. Kisbánya. Analyst, L. Zombory, 1934.

2. Felsőbánya. Analyst, L. Loczka, 1928 (J. Krenner, loc. cit.). Also Zn 0·24, Cu 0·06, Pb 0·94, As trace.

3. Aranyidka. Analyst, J. Pettko, 1847 (A. Löwe, loc. cit.).

4. Bohutin, near Příbram, Bohemia. Analyst, R. Vambera, 1898 (A. Hofmann, Sitz.-Ber. böhm. Gesell. Wiss., 1898, vol. II for 1897, no. 49). Also Pb trace.

5. San Antonio, Lower California, Mexico. Analyst, — Freese, 1866 (C. F. Rammelsberg, Zeits. Deutsch. Geol. Gesell., 1866, vol. 18, p. 244; Handbuch d. Mineralchemie, 2nd edit., 1875, part 2, p. 86).

A new meteoric stone from Silverton, New South Wales.

(With Plate XXIII.)

By L. J. Spencer, M.A., Sc.D., F.R.S.
Keeper of Minerals in the British Museum of Natural History.

[Read June 7, 1934.]

UNFORTUNATELY nothing is known of the history of this stone. It was found in 1933 by Mr. R. Bedford in the old museum at Port Adelaide in South Australia. Attached to the specimen is a small label with the number 23, and accompanying it was a card giving in faded writing the information '(23) Meteoric stone from Silverton'. The Port Adelaide Museum has been in a neglected condition for thirty years, and recently it has been decided to reorganize it as a Nautical Museum, and to discard all mineral and miscellaneous material. The work of clearing up and rearrangement was undertaken by Mr. Bedford, and, the museum having no funds, he received in exchange for his services much of the discarded material for the Kyancutta Museum. The nice little meteoric stone was found by him buried in a heap of mineral junk and dust in one of the cases. It is now the property of the Kyancutta Museum in South Australia, which is actively administered by Mr. Bedford.

The period of greatest activity of the Port Adelaide Museum was between 1880 and 1890. The label accompanying the stone appears to be about that date, and no doubt the specimen was added to the collection sometime during that period. This corresponds with the time of the discovery of the rich ore-deposits at Broken Hill in the Silverton district, in New South Wales near the border of South Australia. Silverton (lat. 31° 53′ S., long. 141° 12′ E.) was surveyed and proclaimed a town in 1883, and Broken Hill was pegged out in the same year. The date of finding of the stone may then have been about 1883 or a few years later; but there is no definite information, and nothing is known of the fall of a meteorite in that district.

The stone was kindly sent by Mr. Bedford to the British Museum for inspection, with permission to cut off, if necessary, a portion for

examination, and he has generously allowed a fragment (32 grams) to be kept for the British Museum collection of meteorites.

It is a complete stone entirely covered with crust and showing no sign of fracture or damage. The delicate surface markings show very clearly the oriented flight of the stone through the earth's atmosphere. The stone must have been collected very soon after its fall. The

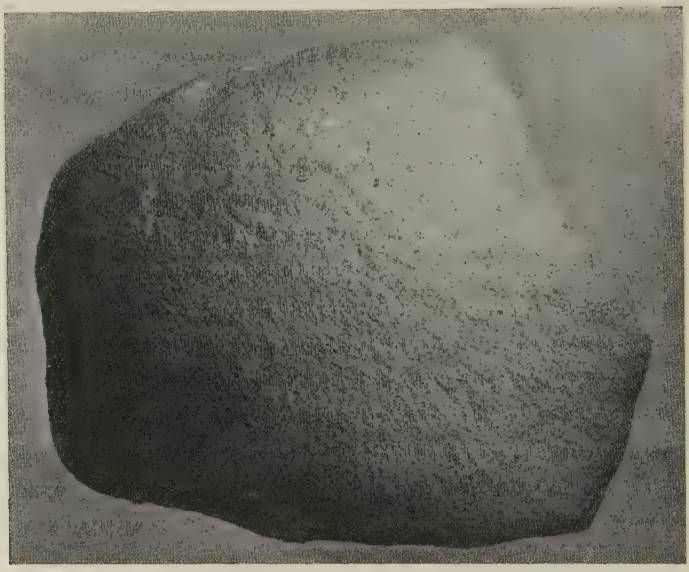


Fig. 1. Meteoric stone from Silverton, New South Wales. Photograph of the uncoloured plaster cast, showing the radiating streaks on the front surface. Same size.

general shape suggests a segment of a ball, which, if complete, would be about 10 cm. in diameter. The front spherical surface is smooth except for delicate streaks in the crust radiating from the centre. These streaks pass over the edges like a cascade, giving a line of a thicker blebby crust, and showing very clearly the flow of molten material from front to back. The back of the stone is bounded by three surfaces meeting in an apex which lies directly behind the centre of the front surface. One of these is flat with a thick blebby and corrugated crust. The two other surfaces are less even and have a thinner crust, which shows the blebby character only at the edges adjoining the front of the stone. These two are evidently later fractures while the stone was travelling through the air. Pittings

and 'thumb-marks' often seen on meteoric stones are not present. The dimensions across the front of the stone are 8·2 and 6·5 cm., and the thickness from front to back is 5·0 cm. In colour the stone is dull black with some indistinct dark brown patches. The weight was 350·73 grams (rather over $\frac{3}{4}$ lb.).

Before making a mould of the stone and weighing it in water, it was coated with a film of vinyl acetate, which has been found to be a good preservative for meteorites. Excellent casts were made by

Fig. 2. Meteoric stone from Silverton, New South Wales. Photograph of the actual stone; side view showing the flow of material from the rounded front towards the two back surfaces of later fracture. Same size.

Mr. F. O. Barlow. Fig. 1 is from a photograph of the uncoloured cast which shows rather more clearly the radiating streaks on the crust than would be shown by a photograph of the dark stone. Fig. 2 is a side-view photograph of the actual stone. The specific gravity of the whole stone was determined by hydrostatic weighing to be 3·31. This is, however, a low value for the material. The stone is somewhat porous, and when a fragment is immersed in water there is an escape of air bubbles.

The stone was easily cut with a diamond-charged slitting disk, giving a smooth surface. The metallic inclusions took a good polish, but the stony portion, although apparently compact, did not polish. A slice 1 mm. thick was then cut for the preparation of micro-sections, but this broke into pieces owing to the friability of the stone. Fragments readily crumble when rubbed between the fingers.

The section of the stone (plate XXIII, fig. 3) shows the dull black crust $\frac{1}{2}$–1 mm. thick, with no appreciable difference in thickness and character on the front and back surfaces. The crust is magnetic. Embedded in it are several particles of metal still showing jagged outlines and sometimes extending to the outer surface of the meteorite. There are also several small cavities with roundish or irregular outlines. Inside the crust there is an iron-stained zone up to $\frac{1}{2}$ cm. wide of a light brown colour. This represents a slight oxidation and rusting which no doubt took place under moist conditions between the time when the stone fell and when it was found. This could perhaps have been produced by a single shower of rain. Small iron-stained patches are also seen throughout the section, mostly around the particles of nickel-iron. The irregular distribution, small amount, and jagged outlines of the particles of nickel-iron are shown in fig. 4; the largest area measures 2 mm. across. Troilite is present as smaller and rounder grains. The stony portion is light grey in colour. Chondrules are to be seen, but they are not very conspicuous. They are white and usually round with a diameter of 1 to 2 mm.; the largest (not in the section figured) is oval, measuring $4\frac{1}{2} \times 3$ mm.

Micro-sections show a confused aggregate of broken crystals, mostly as fine particles, with some larger fissured crystals of olivine and enstatite (or hypersthene); also a few chondrules and fragments of chondrules of fibrous enstatite and of porphyritic olivine. Only a small amount of felspar is recognizable. The black crust is opaque.

The stone may be classed as a white hypersthene-olivine-chondrite of the Baroti type.[1] It is very similar to the stone seen to fall on March 9, 1923, at Ashdon in Essex.[2] In shape and surface markings it is also similar to the Ashdon stone, but about one-quarter the size.

Explanation of Plate XXIII.

Section of the meteoric stone from Silverton, New South Wales. $\times 2\frac{1}{3}$.
The right-hand edge is the front of the stone.

Fig. 3. The stony portion in the reflecting position, showing the black crust and the chondrules.

Fig. 4. The same section photographed with the metallic particles in the reflecting position.

[1] G. T. Prior, Min. Mag., 1916, vol. 18, p. 30; 1920, vol. 19, p. 61.
[2] G. T. Prior, Min. Mag., 1923, vol. 20, p. 131.

Fig. 3.

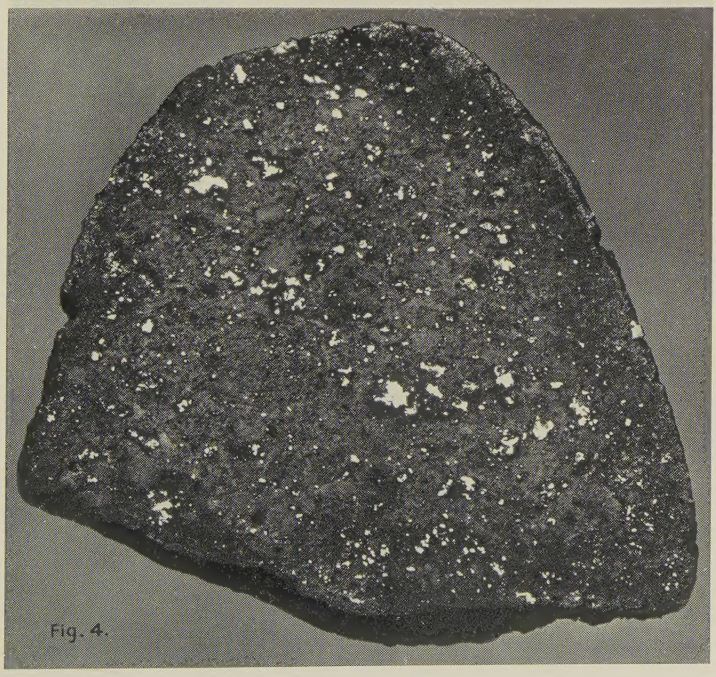


Fig. 4.

L. J. Spencer: Meteoric Stone, Silverton, New South Wales.